# Heat Treatment

Heat Treatment

**Recommended Procedures and Temperatures Applicable to:**
**Corrosion-resistant Alloys**
**High-temperature Alloys**
**Wear & Corrosion-resistant Alloy**

The heat treatment of the HAYNES® and HASTELLOY® alloys is a very important topic. In the production of these wrought materials, there are many hot- and cold-reduction steps, between which intermediate heat treatments are necessary, to restore the optimum properties, in particular ductility. In the case of the corrosion-resistant alloys, these intermediate heat treatments are generally solution-annealing treatments. In the case of the high-temperature alloys, this is not necessarily so.

Once the materials have reached their final sizes, they are given a final anneal. This is usually a solution-anneal; however, a few high-temperature alloys (HTA) are final annealed at an adjusted temperature, to control grain size, or some other microstructural feature.

Subsequent fabrication of these as-supplied materials can again involve hot- or cold-working, as discussed in the Hot-working and Cold-working sections of this guide. Again, working often involves steps, with intermediate annealing (normally solution-annealing for the CRA materials) treatments to restore ductility. Beyond that, fabricated components will require a final anneal (normally a solution-anneal for the CRA materials), to restore optimum properties prior to use, or (in the case of the age-hardenable alloys) to prepare them for age-hardening.

**Applicable to:**
**Corrosion-resistant Alloys**

The compositions of the corrosion-resistant alloys (CRA) comprise a nickel base, substantial additions of chromium and/or molybdenum (in some cases partially replaced by tungsten), small additions such as copper (to enhance resistance to certain media) and iron (to allow the use of less expensive raw materials), and minor additions such as aluminum and manganese, which help remove deleterious elements such as oxygen and sulfur, during melting. As-supplied, they generally exhibit single phase (face-centered cubic, or gamma) wrought microstructures.

In most cases, the presence of a single phase microstructure in as-supplied (CRA) materials is due to a high temperature, solution-annealing treatment, followed by quenching (rapid cooling), to “lock-in” the high-temperature structure. Left to cool slowly, most of these alloys would contain second phases (albeit in small amounts), commonly within the structural grain boundaries, as a result of the fact that the combined contents of the alloying additions exceed their solubility limits.

This is exacerbated by the fact that, despite sophisticated melting techniques and procedures, traces of unwanted elements (with very low solubility), such as carbon and silicon, can be present. Fortunately, solution-annealing, followed by quenching (by water or cold gas), solves this problem also.

The corrosion-resistant alloys are usually supplied in the solution-annealed condition, and their normal solution-annealing temperatures are given in the table below. They represent temperatures at which phases other than gamma (and, in rare cases, primary carbides and/or nitrides) dissolve, yet provide grain sizes within the range known to impart good mechanical properties. Primary carbides and/or nitrides are seen in C-4 alloy, due to the presence of titanium.

In the case of the corrosion-resistant alloys (CRA), the terms solution-annealed and mill-annealed (MA) are generally synonymous; however, the temperatures used in continuous hydrogen-annealing furnaces (in sheet production) are adjusted to compensate for the line speeds (hence time at temperature).

**Solution-annealing Temperatures of the Corrosion-resistant Alloys (CRA)**

| Alloy | Solution-annealing Temperature* | | Type of Quench |
|---|---|---|---|
| | °F | °C | - |
| B-3® | 1950 | 1066 | WQ or RAC |
| C-4 | 1950 | 1066 | WQ or RAC |
| C-22® | 2050 | 1121 | WQ or RAC |
| C-22HS® | 1975 | 1079 | WQ or RAC |
| C-276 | 2050 | 1121 | WQ or RAC |
| C-2000® | 2100 | 1149 | WQ or RAC |
| G-30® | 2150 | 1177 | WQ or RAC |
| G-35® | 2050 | 1121 | WQ or RAC |
| HYBRID-BC1® | 2100 | 1149 | WQ or RAC |

*Plus or Minus 25°F (14°C)
WQ = Water Quench (Preferred); RAC = Rapid Air Cool

There are no specific rules regarding the times required to heat up, then anneal, the corrosion-resistant alloys (CRA), since there are many types of furnace, involving different modes of loading, unloading, and operation. There are only general guidelines.

The temperature of the work-piece being annealed should be measured with an attached thermocouple, and recording of the annealing time should begin only when the entire section of the work-piece has reached the recommended annealing temperature. It should be remembered that the center of the section takes longer to reach the annealing temperature than the surface.

**The general guidelines regarding time are:**

- Normally, once the whole of the workpiece is at the annealing temperature, the annealing time should be between 10 and 30 minutes, depending upon the section thickness.
- The shorter times within this range should be used for thin sheet components.
- The longer times should be used for thick (heavier) sections.

Rapid cooling is essential after annealing, to prevent the nucleation and growth of deleterious second phase precipitates in the microstructure, particularly at the grain boundaries. Water quenching is preferred, and highly recommended for materials thicker than 3/8 in (9.5 mm). Rapid air cooling has been used for thin sections. The time between removal from the furnace and the start of quenching must be as short as possible (and certainly less than three minutes).

Special precautions are necessary with B-3® alloy. Although more stable than other nickel-molybdenum alloys (particularly its predecessor, B-2® alloy), it is still prone to significant, deleterious, microstructural changes in the temperature range 1100-1500°F (593-816°C), especially after being cold-worked. Thus, care must be taken to avoid exposing B-3® alloy to temperatures within this range for any length of time. B-3® alloy should be annealed in furnaces pre-heated to the annealing temperature (1950°F/1066°C), and with sufficient thermal capacity to ensure rapid recovery of the temperature after loading of the furnace with the B-3® work-piece.

One of the potential problems associated with these microstructural changes (which can occur during heating to the annealing temperature) in the nickel-molybdenum (B-type) alloys is cracking due to residual stresses, in cold-worked material. Shot peening of the knuckle radius and straight flange regions of cold-formed heads, to lower residual tensile stress patterns, has been found to be very beneficial in avoidance of such problems.

**Applicable To:**
**High-temperature Alloys**

The high-temperature alloys (HTA), whether based on nickel, cobalt, or a mixture of nickel, cobalt, and iron, are compositionally much more complicated. However, as in the CRA alloys, chromium is an important alloying element, enabling the formation of protective, surface films (particularly oxides) in hot gases.

Large atoms such as molybdenum and tungsten are used to provide solid-solution strength to many of the high-temperature alloys. Those relying on age-hardening for strength include significant quantities of elements such as aluminum, titanium, and niobium (columbium), which can form extremely fine precipitates of second phases (“gamma prime” and “gamma double prime”) known to be very effective strengtheners.

Aluminum can play another role in the high temperature alloys, and that is to modify the protective films (oxides, in particular) that form on the surfaces of these materials at high-temperatures, in the presence of oxygen, etc. Indeed, aluminum oxide is very adherent, stable, and protective.

Unlike the CRA materials, in which carbon is generally a negative actor, the high-temperature HAYNES® and HASTELLOY® (HTA) alloys rely upon deliberate carbon additions, or rather the carbides they induce in the microstructures, to provide the necessary levels of strength (particularly creep strength) for high-temperature service. In some cases, these carbides form during solidification of the materials (primary carbides). In other cases, they form during high-temperature exposure, in the solid state (secondary carbides).

As a consequence of the need for specific carbide types and morphologies in the HTA materials, annealing is a much more complicated subject, especially between steps in the manufacturing and fabrication processes.

**The high-temperature HAYNES® and HASTELLOY® alloys are normally supplied in the solution-annealed condition, which is attained by heat treatment at the following temperatures (or within the specified ranges):**

**Solution-annealing Temperatures of the High-temperature Alloys (HTA)**

| Alloy | Solution-annealing Temperature/Range | | Type of Quench |
|---|---|---|---|
| | °F | °C | - |
| 25 | 2150-2250 | 1177-1232 | WQ or RAC |
| 75 | 1925* | 1052* | WQ or RAC |
| 188 | 2125-2175 | 1163-1191 | WQ or RAC |
| 214® | 2000 | 1093 | WQ or RAC |
| 230® | 2125-2275 | 1163-1246 | WQ or RAC |
| 242® | 1900-2050 | 1038-1121 | WQ or RAC |
| 244® | 2000-2100 | 1093-1149 | WQ or RAC |
| 263 | 2100 ± 25 | 1149 ± 14 | WQ or RAC |
| 282® | 2050-2100 | 1121-1149 | WQ or RAC |

| | | | |
|---|---|---|---|
| 556® | 2125-2175 | 1163-1191 | WQ or RAC |
| 625 | 2000-2200 | 1093-1204 | WQ or RAC |
| 718 | 1700-1850** | 927-1010** | WQ or RAC |
| HR-120® | 2150-2250 | 1177-1232 | WQ or RAC |
| HR-160® | 2025-2075 | 1107-1135 | WQ or RAC |
| HR-224® | | | WQ or RAC |
| HR-235® | 2075-2125 | 1135-1163 | WQ or RAC |
| MULTIMET® | 2150 | 1177 | WQ or RAC |
| N | 2150 | 1177 | WQ or RAC |
| R-41 | 2050 | 1121 | WQ or RAC |
| S | 1925-2075 | 1052-1135 | WQ or RAC |
| W | 2165 | 1185 | WQ or RAC |
| WASPALOY | 1975 | 1079 | WQ or RAC |
| X | 2125-2175 | 1163-1191 | WQ or RAC |
| X-750 | 1900* | 1038* | WQ or RAC |

WQ = Water Quench (Preferred); RAC = Rapid Air Cool
*Bright (Hydrogen) Annealing Temperature
**Not Strictly a Solution-annealing Temperature Range (More a Preparatory Annealing Temperature Range)

In the solution-annealed condition, the microstructures of the high-temperature alloys (HTA) generally consist of primary carbides dispersed in a gamma phase (face-centered cubic) matrix, with essentially clean (precipitate-free) grain boundaries. For the solid-solution strengthened alloys, this is usually the optimum condition for both high-temperature service, and for room temperature fabricability.
Although the HAYNES® and HASTELLOY® alloys should not be subjected to stress relief treatments at the sort of temperatures used for the steels and stainless steels, for fear of causing the precipitation of undesirable second phases (particularly in the alloy grain boundaries), some lower annealing temperatures have been used for the high-temperature alloys (HTA) between processing steps, to restore the ductility of partially-fabricated workpieces. These so-called intermediate annealing temperatures should be used with caution, since they too are likely to result in the aforementioned grain boundary precipitation. Some minimum, intermediate annealing temperatures are given in the following table (for selected solid-solution strengthened HTA materials):

**Minimum Intermediate Annealing Temperatures (HTA)**

| Alloy | Minimum Intermediate Annealing Temperature | |
|---|---|---|
| | °F | °C |
| 25 | 2050 | 1121 |
| 188 | 2050 | 1121 |
| 230® | 2050 | 1121 |
| 556® | 1900 | 1038 |
| 625 | 1700 | 927 |
| HR-120® | 1950 | 1066 |
| HR-160® | 1950 | 1066 |

| | | |
|---|---|---|
| S | 1750 | 954 |
| X | 1850 | 1010 |

Whether an intermediate annealing temperature (rather than a solution-annealing temperature) is appropriate between processing steps will depend upon the alloy and the effects of the lower temperature upon microstructure, and upon the nature of the subsequent operation. These issues must be studied carefully, and advice sought.

**Annealing During Cold (or Warm) Forming**

**Applicable To:**
**High-temperature Alloys**

The response of the HAYNES® and HASTELLOY® high-temperature alloys (HTA) to heat treatment is very dependent upon the condition of the material prior to the treatment. When the material is not in a cold- or warm-worked condition, the principal response is usually a change in the amount and morphology of the secondary carbide phases. Other minor effects might occur, but the grain structure normally remains the same (in the absence of prior cold or warm work).

When these alloys have been subjected to cold- or warm-work, the application of a solution or intermediate anneal will almost always alter the grain structure. Moreover, the amount of prior cold- or warm-work will significantly affect the grain structure, and consequently the mechanical properties of the material.

The following table indicates the effects of heat-treatments (of 5 minutes duration) at various temperatures upon the grain sizes of sheets of several high temperature alloys, subjected to different levels of cold-work.

**Effects of Cold-work and Heat Treatment Temperature on Grain Size**

| Cold-work | Heat Treatment Temperature | | ASTM Grain Size Produced | | | |
|---|---|---|---|---|---|---|
| % | °F | °C | 25 | 230® | 556® | X |
| 0 | None | | 3.5-4 | 5-6 | 5-6 | 4-5 |
| 10 | 1850 | 1010 | NA | NA | NR | NR |
| | 1950 | 1066 | NR | NR | NR | NR |
| | 2050 | 1121 | NR | NFR | 5-5.5 | 5-7 |
| | 2150 | 1177 | 4-4.5 | 4-7 | 5-5.5 | NA |
| | 2250 | 1232 | 3-4.5 | 6.5-7 | NA | NA |
| 15 | 1950 | 1066 | 7 | NA | NA | NA |
| | 2050 | 1121 | 6-7 | NA | NA | NA |
| | 2150 | 1177 | 5-7 | NA | NA | NA |
| | 2250 | 1232 | 3-4.5 | NA | NA | NA |
| 20 | 1850 | 1010 | NA | NA | NR | NFR |
| | 1950 | 1066 | 7-8 | NFR | NR | NFR |
| | 2050 | 1121 | 7-8 | 8-8.5 | 7.5-8.5 | 7-8 |
| | 2150 | 1177 | 4.5-7 | 7.5-8 | 6-6.5 | NA |
| | 2250 | 1232 | 2.5-4.5 | 7-7.5 | NA | NA |

| | | | | | | |
|---|---|---|---|---|---|---|
| 25 | 1950 | 1066 | 7.5-8 | NA | NA | NA |
| | 2050 | 1121 | 7.5-8 | NA | NA | NA |
| | 2150 | 1177 | 4 | NA | NA | NA |
| | 2250 | 1232 | 3.5 | NA | NA | NA |
| 30 | 1850 | 1010 | NA | NA | NFR | NFR |
| | 1950 | 1066 | NA | 8-9 | 7.5-9.5 | 8-10 |
| | 2050 | 1121 | NA | 9-10 | 7-7.5 | 7.5-9.5 |
| | 2150 | 1177 | NA | 8.5-9 | 4.5-6.5 | NA |
| | 2250 | 1232 | NA | 6-7 | NA | NA |
| 40 | 1850 | 1010 | NA | NA | 7.5-9.5 | 8-9 |
| | 1950 | 1066 | NA | 9.5-10 | 8-9.5 | 8-10 |
| | 2050 | 1121 | NA | 9-10 | 7-9 | 9.5-10 |
| | 2150 | 1177 | NA | 8.5-9 | 4.5-6.5 | NA |
| | 2250 | 1232 | NA | 4-7 | NA | NA |
| 50 | 1850 | 1010 | NA | NA | 9-10 | 8.5-10 |
| | 1950 | 1066 | NA | 9-10 | 8.5-10 | 8.5-10 |
| | 2050 | 1121 | NA | 9-10 | 8-9.5 | 8.5-10 |
| | 2150 | 1177 | NA | 9-9.5 | 5.5-6 | NA |
| | 2250 | 1232 | NA | 5.5-6.5 | NA | NA |

NA=Not Available
NR= No Recrystallization Observed
NFR=Not Fully Recrystallized

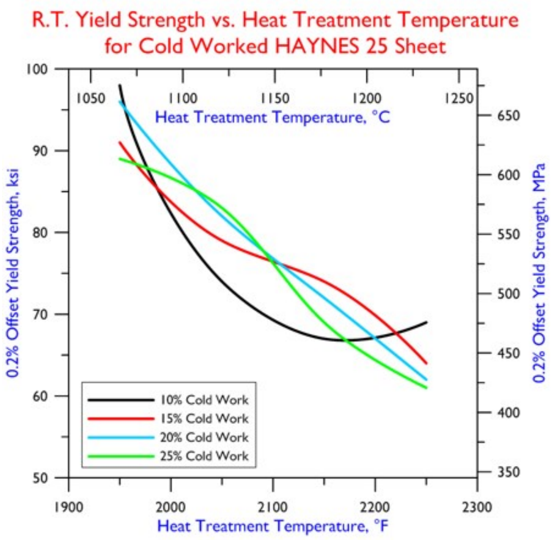
The effects of cold-work plus heat treatment at various temperatures upon the mechanical properties of several solid solution strengthened, high temperature HAYNES® and HASTELLOY® alloys are shown in the following tables and figures.

### Effects of Cold-work and Heat Treatment Temperature on the Room Temperature Mechanical Properties of HAYNES® 25 Sheet

| Cold-work | Heat Treatment* Temperature | | 0.2% Offset Yield Strength | | Ultimate Tensile Strength | | Elongation | Hardness |
|---|---|---|---|---|---|---|---|---|
| % | °F | °C | ksi | MPa | ksi | MPa | % | HRC |
| No Cold-work | No Heat Treatment | | 68 | 469 | 144 | 993 | 58 | 24 |
| 10 | No Heat Treatment | | 124 | 855 | 182 | 1255 | 37 | 36 |
| 15 | No Heat Treatment | | 149 | 1027 | 178 | 1227 | 28 | 40 |
| 20 | No Heat Treatment | | 151 | 1041 | 193 | 1331 | 18 | 42 |
| 25 | No Heat Treatment | | 184 | 1269 | 232 | 1600 | 15 | 44 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 10 | 1950 | 1066 | 98 | 676 | 163 | 1124 | 39 | 32 |
| 15 | 1950 | 1066 | 91 | 627 | 167 | 1151 | 44 | 30 |
| 20 | 1950 | 1066 | 96 | 662 | 171 | 1179 | 41 | 32 |
| 25 | 1950 | 1066 | 89 | 614 | 169 | 1165 | 44 | 32 |
| 10 | 2050 | 1121 | 74 | 510 | 157 | 1082 | 53 | 27 |
| 15 | 2050 | 1121 | 79 | 545 | 161 | 1110 | 52 | 28 |
| 20 | 2050 | 1121 | 82 | 565 | 165 | 1138 | 48 | 31 |
| 25 | 2050 | 1121 | 83 | 572 | 166 | 1145 | 48 | 30 |
| 10 | 2150 | 1177 | 67 | 462 | 148 | 1020 | 63 | 21 |
| 15 | 2150 | 1177 | 74 | 510 | 156 | 1076 | 55 | 26 |
| 20 | 2150 | 1177 | 72 | 496 | 154 | 1062 | 59 | 26 |
| 25 | 2150 | 1177 | 69 | 476 | 149 | 1027 | 62 | 25 |
| 10 | 2250 | 1232 | 69 | 476 | 144 | 993 | 64 | 95 |
| 15 | 2250 | 1232 | 64 | 441 | 142 | 979 | 68 | 97 |
| 20 | 2250 | 1232 | 62 | 427 | 135 | 931 | 69 | 97 |
| 25 | 2250 | 1232 | 61 | 421 | 138 | 951 | 70 | 96 |

*5 Minutes Duration + Rapid Air Cool
Tensile Results are Averages of 2 or More Tests
HRC= Hardness Rockwell "C"

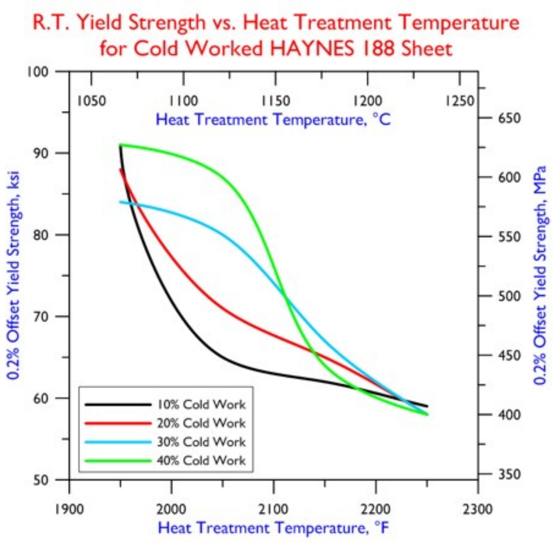



## Effects of Cold-work and Heat Treatment Temperature on the Room Temperature Mechanical Properties of HAYNES® 188 Sheet

| Cold-work | Heat Treatment* Temperature | | 0.2% Offset Yield Strength | | Ultimate Tensile Strength | | Elongation | Hardness |
|---|---|---|---|---|---|---|---|---|
| % | °F | °C | ksi | MPa | ksi | MPa | % | HR B/C |
| No Cold-work | No Heat Treatment | | 67 | 462 | 137 | 945 | 54 | 98 HRB |
| 10 | No Heat Treatment | | 106 | 731 | 151 | 1041 | 45 | 32 HRC |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 20 | No Heat Treatment | | 133 | 917 | 166 | 1145 | 28 | 37 HRC |
| 30 | No Heat Treatment | | 167 | 1151 | 195 | 1344 | 13 | 41 HRC |
| 40 | No Heat Treatment | | 177 | 1220 | 215 | 1482 | 10 | 44 HRC |
| 10 | 1950 | 1066 | 91 | 627 | 149 | 1027 | 41 | 30 HRC |
| 20 | 1950 | 1066 | 88 | 607 | 153 | 1055 | 41 | 28 HRC |
| 30 | 1950 | 1066 | 84 | 579 | 158 | 1089 | 41 | 30 HRC |
| 40 | 1950 | 1066 | 91 | 627 | 163 | 1124 | 40 | 31 HRC |
| 10 | 2050 | 1121 | 65 | 448 | 143 | 986 | 50 | 22 HRC |
| 20 | 2050 | 1121 | 71 | 490 | 149 | 1027 | 47 | 25 HRC |
| 30 | 2050 | 1121 | 80 | 552 | 155 | 1069 | 44 | 28 HRC |
| 40 | 2050 | 1121 | 87 | 600 | 159 | 1096 | 43 | 30 HRC |
| 10 | 2150 | 1177 | 62 | 427 | 140 | 965 | 55 | 96 HRB |
| 20 | 2150 | 1177 | 65 | 448 | 141 | 972 | 53 | 97 HRB |
| 30 | 2150 | 1177 | 67 | 462 | 143 | 986 | 52 | 99 HRB |
| 40 | 2150 | 1177 | 64 | 441 | 141 | 972 | 56 | 97 HRB |
| 10 | 2250 | 1232 | 59 | 407 | 132 | 910 | 59 | 95 HRB |
| 20 | 2250 | 1232 | 58 | 400 | 130 | 896 | 63 | 94 HRB |
| 30 | 2250 | 1232 | 58 | 400 | 131 | 903 | 63 | 93 HRB |
| 40 | 2250 | 1232 | 58 | 400 | 132 | 910 | 62 | 93 HRB |

*5 Minutes Duration + Rapid Air Cool
Tensile Results are Averages of 2 or More Tests
HRB= Hardness Rockwell "B"
HRC= Hardness Rockwell "C"

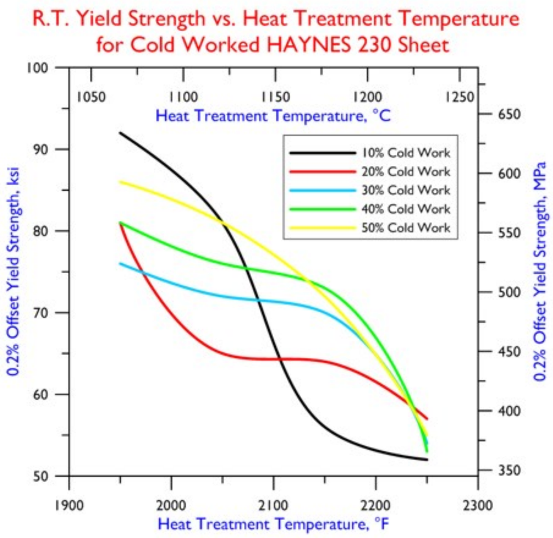



**Effects of Cold-work and Heat Treatment Temperature on the Room Temperature Mechanical Properties of HAYNES® 230® Sheet**

| | Heat | 0.2% Offset | Ultimate | | |
|---|---|---|---|---|---|

| Cold-work | Treatment* Temperature | | Yield Strength | | Tensile Strength | | Elongation | Hardness |
|---|---|---|---|---|---|---|---|---|
| % | °F | °C | ksi | MPa | ksi | MPa | % | HR B/C |
| No Cold-work | No Heat Treatment | | 62 | 427 | 128 | 883 | 47 | 95 HRB |
| 10 | No Heat Treatment | | 104 | 717 | 145 | 1000 | 32 | 28 HRC |
| 20 | No Heat Treatment | | 133 | 917 | 164 | 1131 | 17 | 35 HRC |
| 30 | No Heat Treatment | | 160 | 1103 | 188 | 1296 | 10 | 39 HRC |
| 40 | No Heat Treatment | | 172 | 1186 | 202 | 1393 | 8 | 40 HRC |
| 50 | No Heat Treatment | | 185 | 1276 | 215 | 1482 | 6 | 42 HRC |
| 10 | 1950 | 1066 | 92 | 634 | 144 | 993 | 33 | 24 HRC |
| 20 | 1950 | 1066 | 81 | 558 | 142 | 979 | 36 | 26 HRC |
| 30 | 1950 | 1066 | 76 | 524 | 142 | 979 | 36 | 99 HRB |
| 40 | 1950 | 1066 | 81 | 558 | 146 | 1007 | 32 | 23 HRC |
| 50 | 1950 | 1066 | 86 | 593 | 148 | 1020 | 35 | 24 HRC |
| 10 | 2050 | 1121 | 81 | 558 | 139 | 958 | 37 | 98 HRB |
| 20 | 2050 | 1121 | 65 | 448 | 136 | 938 | 39 | 97 HRB |
| 30 | 2050 | 1121 | 72 | 496 | 140 | 965 | 38 | 99 HRB |
| 40 | 2050 | 1121 | 76 | 524 | 142 | 979 | 36 | 99 HRB |
| 50 | 2050 | 1121 | 81 | 558 | 144 | 993 | 36 | 23 HRC |
| 10 | 2150 | 1177 | 56 | 386 | 130 | 896 | 44 | 92 HRB |
| 20 | 2150 | 1177 | 64 | 441 | 134 | 924 | 40 | 96 HRB |
| 30 | 2150 | 1177 | 70 | 483 | 138 | 951 | 39 | 98 HRB |
| 40 | 2150 | 1177 | 73 | 503 | 139 | 958 | 38 | 98 HRB |
| 50 | 2150 | 1177 | 72 | 496 | 138 | 951 | 39 | 98 HRB |
| 10 | 2250 | 1232 | 52 | 359 | 125 | 862 | 47 | 92 HRB |
| 20 | 2250 | 1232 | 57 | 393 | 128 | 883 | 45 | 92 HRB |
| 30 | 2250 | 1232 | 54 | 372 | 126 | 869 | 48 | 92 HRB |
| 40 | 2250 | 1232 | 53 | 365 | 126 | 869 | 47 | 91 HRB |
| 50 | 2250 | 1232 | 55 | 379 | 128 | 883 | 46 | 89 HRB |

*5 Minutes Duration + Rapid Air Cool
Tensile Results are Averages of 2 or More Tests
HRB= Hardness Rockwell "B"
HRC= Hardness Rockwell "C"




**Effects of Cold-work and Heat Treatment Temperature on the Room Temperature Mechanical Properties of HAYNES® 625 Sheet**

| Cold-work | Heat Treatment* Temperature | | 0.2% Offset Yield Strength | | Ultimate Tensile Strength | | Elongation | Hardness |
|---|---|---|---|---|---|---|---|---|
| % | °F | °C | ksi | MPa | ksi | MPa | % | HR B/C |
| No Cold-work | No Heat Treatment | | 70 | 483 | 133 | 917 | 46 | 97 HRB |
| 10 | No Heat Treatment | | 113 | 779 | 151 | 1041 | 30 | 32 HRC |
| 20 | No Heat Treatment | | 140 | 965 | 169 | 1165 | 16 | 37 HRC |
| 30 | No Heat Treatment | | 162 | 1117 | 191 | 1317 | 11 | 40 HRC |
| 40 | No Heat Treatment | | 178 | 1227 | 209 | 1441 | 8 | 42 HRC |
| 50 | No Heat Treatment | | 184 | 1269 | 223 | 1538 | 5 | 45 HRC |
| 10 | 1850 | 1010 | 63 | 434 | 134 | 924 | 46 | NA |
| 20 | 1850 | 1010 | 71 | 490 | 138 | 951 | 44 | NA |
| 30 | 1850 | 1010 | 78 | 538 | 141 | 972 | 44 | NA |
| 40 | 1850 | 1010 | 82 | 565 | 141 | 972 | 42 | NA |
| 50 | 1850 | 1010 | 82 | 565 | 141 | 972 | 42 | NA |
| 10 | 1950 | 1066 | 61 | 421 | 133 | 917 | 46 | NA |
| 20 | 1950 | 1066 | 71 | 490 | 137 | 945 | 45 | NA |
| 30 | 1950 | 1066 | 77 | 531 | 140 | 965 | 44 | NA |
| 40 | 1950 | 1066 | 83 | 572 | 142 | 979 | 42 | NA |
| 50 | 1950 | 1066 | 82 | 565 | 141 | 972 | 42 | NA |
| 10 | 2050 | 1121 | 58 | 400 | 128 | 883 | 50 | NA |
| 20 | 2050 | 1121 | 67 | 462 | 135 | 931 | 46 | NA |
| 30 | 2050 | 1121 | 58 | 400 | 127 | 876 | 52 | NA |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 40 | 2050 | 1121 | 72 | 496 | 137 | 945 | 44 | NA |
| 50 | 2050 | 1121 | 61 | 421 | 130 | 896 | 50 | NA |
| 10 | 2150 | 1177 | 52 | 359 | 122 | 841 | 55 | NA |
| 20 | 2150 | 1177 | 54 | 372 | 124 | 855 | 55 | NA |
| 30 | 2150 | 1177 | 53 | 365 | 122 | 841 | 56 | NA |
| 40 | 2150 | 1177 | 52 | 359 | 122 | 841 | 55 | NA |
| 50 | 2150 | 1177 | 51 | 352 | 119 | 820 | 58 | NA |

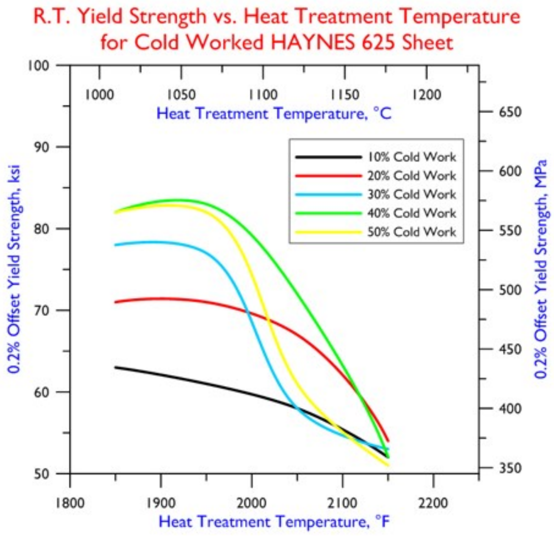
*5 Minutes Duration + Rapid Air Cool

Tensile Results are Averages of 2 or More Tests

NA=Not Available

HRB= Hardness Rockwell "B"

HRC= Hardess Rockwell "C"

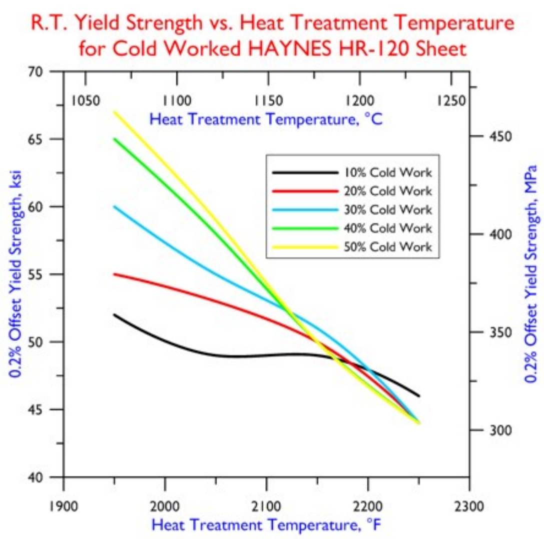



## Effects of Cold-work and Heat Treatment Temperature on the Room Temperature Mechanical Properties of HAYNES HR-120® Sheet

| Cold-work | Heat-treatment* Temperature | | 0.2% Offset Yield Strength | | Ultimate Tensile Strength | | Elongation | Hardness |
|---|---|---|---|---|---|---|---|---|
| % | °F | °C | ksi | MPa | ksi | MPa | % | HR B/C |
| No Cold-work | No Heat Treatment | | 60 | 414 | 113 | 779 | 39 | 93 HRB |
| 10 | No Heat Treatment | | 103 | 710 | 126 | 869 | 26 | 27 HRC |
| 20 | No Heat Treatment | | 129 | 889 | 144 | 993 | 11 | 32 HRC |
| 30 | No Heat Treatment | | 143 | 986 | 157 | 1082 | 6 | 34 HRC |
| 40 | No Heat Treatment | | 159 | 1096 | 179 | 1234 | 6 | 35 HRC |
| 50 | No Heat Treatment | | 166 | 1145 | 186 | 1282 | 5 | 36 HRC |
| 10 | 1950 | 1066 | 52 | 359 | 109 | 752 | 38 | 89 HRB |
| 20 | 1950 | 1066 | 55 | 379 | 111 | 765 | 38 | 92 HRB |
| 30 | 1950 | 1066 | 60 | 414 | 115 | 793 | 38 | 93 HRB |
| 40 | 1950 | 1066 | 65 | 448 | 117 | 807 | 37 | 93 HRB |
| 50 | 1950 | 1066 | 67 | 462 | 118 | 814 | 34 | 93 HRB |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 10 | 2050 | 1121 | 49 | 338 | 108 | 745 | 47 | 88 HRB |
| 20 | 2050 | 1121 | 53 | 365 | 117 | 807 | 41 | 90 HRB |
| 30 | 2050 | 1121 | 55 | 379 | 112 | 772 | 40 | 91 HRB |
| 40 | 2050 | 1121 | 58 | 400 | 114 | 786 | 37 | 91 HRB |
| 50 | 2050 | 1121 | 59 | 407 | 114 | 786 | 37 | 89 HRB |
| 10 | 2150 | 1177 | 49 | 338 | 109 | 752 | 43 | 86 HRB |
| 20 | 2150 | 1177 | 50 | 345 | 109 | 752 | 42 | 87 HRB |
| 30 | 2150 | 1177 | 51 | 352 | 110 | 758 | 43 | 88 HRB |
| 40 | 2150 | 1177 | 50 | 345 | 111 | 765 | 38 | 86 HRB |
| 50 | 2150 | 1177 | 50 | 345 | 110 | 758 | 39 | 82 HRB |
| 10 | 2250 | 1232 | 46 | 317 | 106 | 731 | 46 | 84 HRB |
| 20 | 2250 | 1232 | 44 | 303 | 104 | 717 | 47 | 80 HRB |
| 30 | 2250 | 1232 | 44 | 303 | 103 | 710 | 48 | 80 HRB |
| 40 | 2250 | 1232 | 44 | 303 | 104 | 717 | 45 | 81 HRB |
| 50 | 2250 | 1232 | 44 | 303 | 104 | 717 | 43 | 83 HRB |

*5 Minutes Duration + Rapid Air Cool
Tensile Results are Averages of 2 or More Tests
HRB= Hardness Rockwell "B"
HRC= Hardness Rockwell "C"

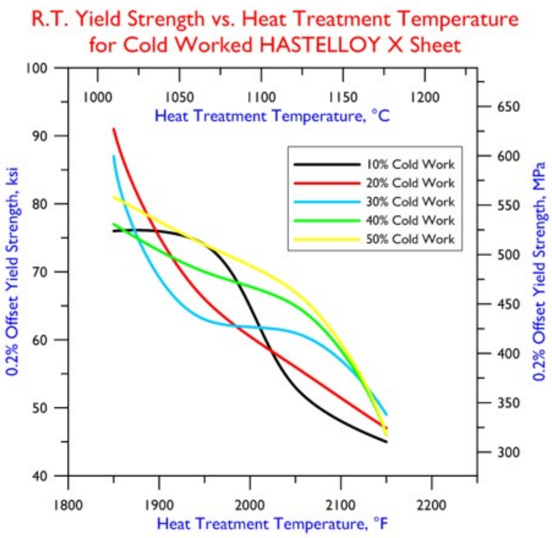



**Effects of Cold-work and Heat Treatment Temperature on the Room Temperature Mechanical Properties of HASTELLOY® X Sheet**

| Cold-work | Heat Treatment* Temperature | | 0.2% Offset Yield Strength | | Ultimate Tensile Strength | | Elongation | Hardness |
|---|---|---|---|---|---|---|---|---|
| % | °F | °C | ksi | MPa | ksi | MPa | % | HR B/C |
| No Cold-work | No Heat Treatment | | 57 | 393 | 114 | 786 | 46 | 89 HRB |
| 10 | No Heat Treatment | | 96 | 662 | 129 | 889 | 29 | 25 HRC |
| 20 | No Heat Treatment | | 122 | 841 | 147 | 1014 | 15 | 31 HRC |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 30 | No Heat Treatment | | 142 | 979 | 169 | 1165 | 10 | 35 HRC |
| 40 | No Heat Treatment | | 159 | 1096 | 186 | 1282 | 8 | 37 HRC |
| 50 | No Heat Treatment | | 171 | 1179 | 200 | 1379 | 7 | 39 HRC |
| 10 | 1850 | 1010 | 76 | 524 | 125 | 862 | 32 | 98 HRB |
| 20 | 1850 | 1010 | 91 | 627 | 132 | 910 | 27 | 23 HRC |
| 30 | 1850 | 1010 | 87 | 600 | 135 | 931 | 28 | 99 HRB |
| 40 | 1850 | 1010 | 77 | 531 | 133 | 917 | 32 | 98 HRB |
| 50 | 1850 | 1010 | 81 | 558 | 135 | 931 | 33 | 99 HRB |
| 10 | 1950 | 1066 | 74 | 510 | 122 | 841 | 34 | 93 HRB |
| 20 | 1950 | 1066 | 66 | 455 | 124 | 855 | 35 | 96 HRB |
| 30 | 1950 | 1066 | 63 | 434 | 126 | 869 | 36 | 96 HRB |
| 40 | 1950 | 1066 | 70 | 483 | 129 | 889 | 35 | 96 HRB |
| 50 | 1950 | 1066 | 74 | 510 | 129 | 889 | 34 | 97 HRB |
| 10 | 2050 | 1121 | 53 | 365 | 119 | 820 | 42 | 89 HRB |
| 20 | 2050 | 1121 | 56 | 386 | 121 | 834 | 40 | 91 HRB |
| 30 | 2050 | 1121 | 61 | 421 | 123 | 848 | 39 | 94 HRB |
| 40 | 2050 | 1121 | 65 | 448 | 125 | 862 | 37 | 94 HRB |
| 50 | 2050 | 1121 | 67 | 462 | 125 | 862 | 38 | 94 HRB |
| 10 | 2150 | 1177 | 45 | 310 | 109 | 752 | 49 | 94 HRB |
| 20 | 2150 | 1177 | 47 | 324 | 111 | 765 | 47 | 87 HRB |
| 30 | 2150 | 1177 | 49 | 338 | 113 | 779 | 46 | 86 HRB |
| 40 | 2150 | 1177 | 46 | 317 | 110 | 758 | 48 | 85 HRB |
| 50 | 2150 | 1177 | 46 | 317 | 110 | 758 | 48 | 84 HRB |

*5 Minutes Duration + Rapid Air Cool
Tensile Results are Averages of 2 or More Tests
HRB= Hardness Rockwell "B"
HRC= Hardness Rockwell "C"




**Age-hardening Treatments for Age-hardenable Alloys**

**Applicable to:**
**Corrosion-resistant Alloys**
**High-temperature Alloys**

| Alloy | No. of Steps | Treatment |
|---|---|---|
| C-22HS® | 2 | 16 hours at 1300°F (704°C), furnace cool to 1125°F (607°C),<br>hold at 1125°F for 32 hours, air cool |
| 242® | 1 | 48 hours* at 1200°F (649°C), air cool |
| 244® | 2 | 16 hours at 1400°F (760°C), furnace cool to 1200°F (649°C),<br>hold at 1200°F for 32 hours, air cool |
| 263 | 1 | 8 hours at 1472°F (800°C), air cool |
| 282® | 2 | 2 hours at 1850°F (1010°C), rapid air cool or air cool,<br>followed by 8 hours at 1450°F (788°C), air cool |
| 718 | 2 | 8 hours at 1325°F (718°C), furnace cool to 1150°F (621°C),<br>hold at 1150°F for 8 hours, air cool |
| R-41 | 1 | 16 hours at 1400°F (760°C), air cool |
| WASPALOY | 3 | 2 hours at 1825°F (996°C), air cool,<br>followed by 4 hours at 1550°F (843°C), air cool,<br>followed by 16 hours at 1400°F (760°C), air cool |
| X-750 | 2 | 8 hours at 1350°F (732°C), furnace cool to 1150°F (621°C),<br>hold at 1150°F for 8 hours, air cool |

*Minimum

To harden/strengthen those materials capable of age hardening, the following treatments are usually applied, assuming the starting material is in the solution-annealed condition. Alternate hardening/strengthening treatments are possible for some of these alloys, depending upon the intended applications and the required strength levels. Please contact Haynes International for details.

**Heating and Cooling Rates**

**Applicable to:**
**Corrosion-resistant Alloys**
**High-temperature Alloys**
**Wear & Corrosion-resistant Alloy**

Heating and cooling of the HAYNES® and HASTELLOY® alloys should generally be as rapid as possible. This is to minimize the precipitation of second phase particles (notably carbides, in the case of the high-temperature alloys) in their microstructures at intermediate temperatures. Rapid heating also preserves stored energy from cold- or warm-work, which can be important to re-crystallization and/or grain growth at the annealing temperature. Indeed, slow heating can result in a finer than desirable grain size, particularly in thin-section components, given limited time at the annealing temperature.

Rapid cooling after solution-annealing is critical, again to prevent the precipitation of second phases, particularly in the microstructural grain boundaries in the approximate temperature range 1000°F to 1800°F (538°C to 982°C). Where practical, and where it is unlikely to cause distortion, a water quench is preferred. It will be noted that cooling from age-hardening treatments (in the case of the age-hardenable, high-temperature alloy components) usually involves air cooling.

The sensitivity of individual alloys to slow cooling varies, but as an example of the effect of cooling rate upon properties, the following table shows the creep life of HAYNES® 188 alloy as a function of the cooling process.

### Effect of Cooling Rate upon the Creep Life of HAYNES® 188 Sheet

| Cooling Process after Solution-annealing at 2150°F (1177°C) | Time to 0.5% Creep for 1600°F/7 ksi (871°C/48 MPa) Test |
|---|---|
| Water Quench | 148 h |
| Air Cool | 97 h |
| Furnace Cool to 1200°F (649°C), then Air Cool | 48 h |

### Holding Time

The times at temperature required for annealing are governed by the need to ensure that all metallurgical reactions are complete, uniformly and throughout the component. As mentioned earlier, the general rules for holding time are at least 30 minutes per inch of thickness in the case of massive workpieces and components, and 10 to 30 minutes (once the entire piece is uniformly at the required annealing temperature) for less massive workpieces and components, depending upon section thickness. Extremely long holding times (such as overnight) are not recommended, since they can be harmful to alloy microstructures and properties.

For continuous annealing of strip or wire, several minutes at temperature will usually suffice.

Time in the furnace will depend on the furnace type and capacity, and the work-piece/component thickness and geometry. To determine when the entire work-piece has reached the required annealing temperature, measurements should be taken using thermocouples attached to the work-piece, where possible.

### Use of a Protective Atmosphere

Most of the HAYNES® and HASTELLOY® alloys can be annealed in oxidizing environments, but will form adherent oxide scales which should normally be removed prior to further processing. For details on scale removal, please refer to the the section on Descaling and Pickling.

Some HAYNES® and HASTELLOY® alloys contain low chromium contents, and require annealing in neutral or slightly reducing atmospheres.

When a bright finish (free from oxide scales) is required, a protective atmosphere, such as low dew point hydrogen, is necessary. Atmospheres of argon and helium have been used, although pronounced tinting is possible with these alternate gases, due to oxygen or water vapor contamination. Annealing in nitrogen or cracked ammonia is not usually recommended, but may be acceptable in certain cases.

Vacuum annealing is generally acceptable, but again some tinting is possible, depending on the vacuum pressure and temperature. Selection of the gas used for forced gas cooling is important: Helium is normally preferred, followed by argon and nitrogen (for some alloys).

### Selection of Heat-Treating Equipment

Most types of industrial furnace are suitable for heat treating the HAYNES® and HASTELLOY® alloys. However, induction heating is not normally recommended, due to inadequate control of the temperature and lack of uniform heating. Heating by torches, welding equipment, and the like is unacceptable. Flame impingement of any type during heat treatment should be avoided.