

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
WASPALLOY	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

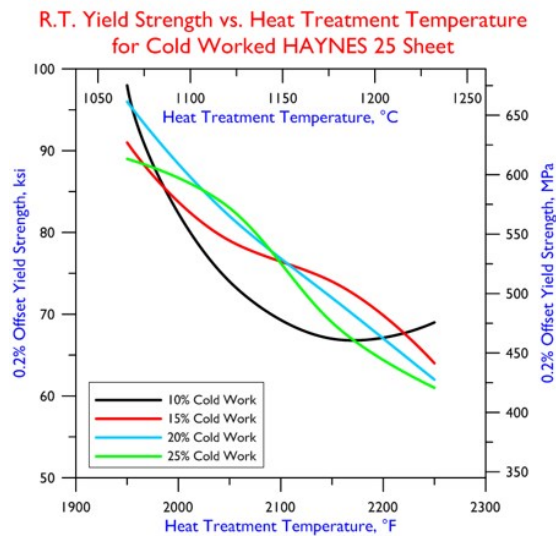
The effects of cold-work plus heat treatment at various temperatures upon the mechanical properties of several solid solution strengthened, high temperature HAYNES[®] and HASTELLOY[®] alloys are shown in the following tables and figures.

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

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

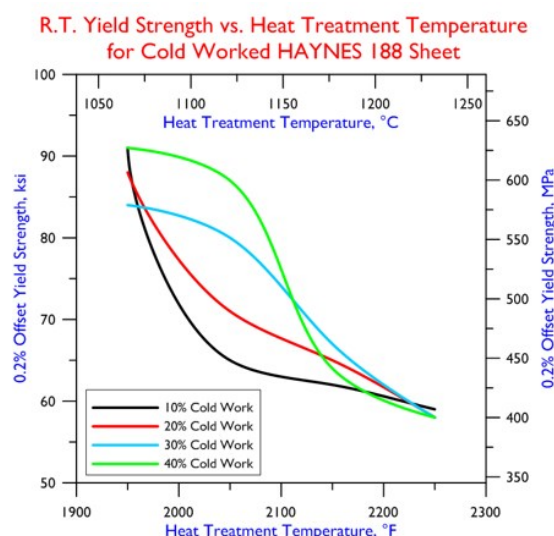
20	No Heat Treatment		133	917	166	1145	28	37 HRC
30	No Heat Treatment		167	1151	195	1344	13	41 HRC
40	No Heat Treatment		177	1220	215	1482	10	44 HRC
10	1950	1066	91	627	149	1027	41	30 HRC
20	1950	1066	88	607	153	1055	41	28 HRC
30	1950	1066	84	579	158	1089	41	30 HRC
40	1950	1066	91	627	163	1124	40	31 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		
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Cold-work	Treatment*		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

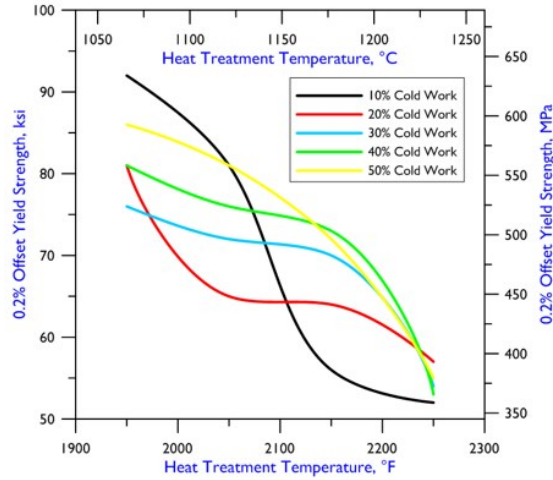
*5 Minutes Duration + Rapid Air Cool

Tensile Results are Averages of 2 or More Tests

HRB= Hardness Rockwell "B"

HRC= Hardness Rockwell "C"

R.T. Yield Strength vs. Heat Treatment Temperature for Cold Worked HAYNES 230 Sheet



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

Cold-work	Heat Treatment*		0.2% Offset Yield Strength		Ultimate Tensile Strength		Elongation	Hardness	
	%	°F	°C	ksi	MPa	ksi			MPa
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

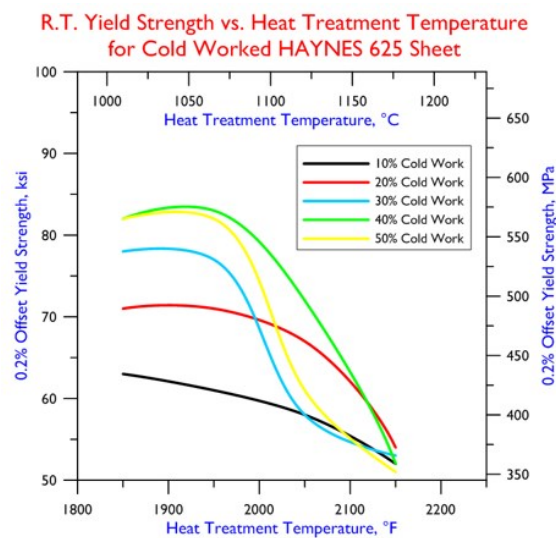
*5 Minutes Duration + Rapid Air Cool

Tensile Results are Averages of 2 or More Tests

NA=Not Available

HRB= Hardness Rockwell "B"

HRC= Hardness 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*		0.2% Offset Yield Strength		Ultimate Tensile Strength		Elongation	Hardness
	%	°F	°C	ksi	MPa	ksi		
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

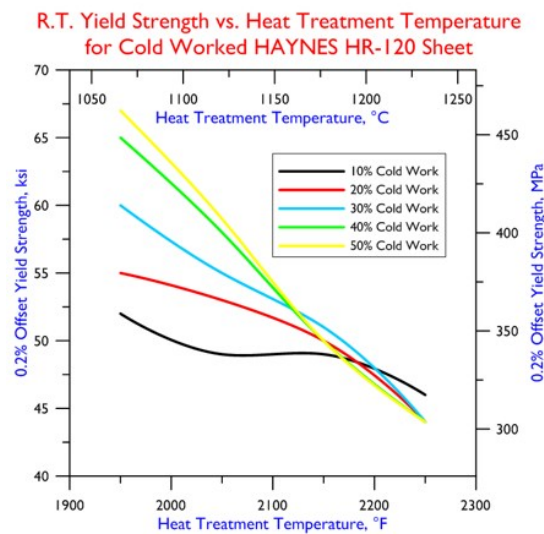
10	2050	1121	49	338	108	745	47	88 HRB
20	2050	1121	53	365	117	807	41	90 HRB
30	2050	1121	55	379	112	772	40	91 HRB
40	2050	1121	58	400	114	786	37	91 HRB
50	2050	1121	59	407	114	786	37	89 HRB
10	2150	1177	49	338	109	752	43	86 HRB
20	2150	1177	50	345	109	752	42	87 HRB
30	2150	1177	51	352	110	758	43	88 HRB
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*		0.2% Offset Yield Strength		Ultimate Tensile Strength		Elongation	Hardness
	%	°F	°C	ksi	MPa	ksi		
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

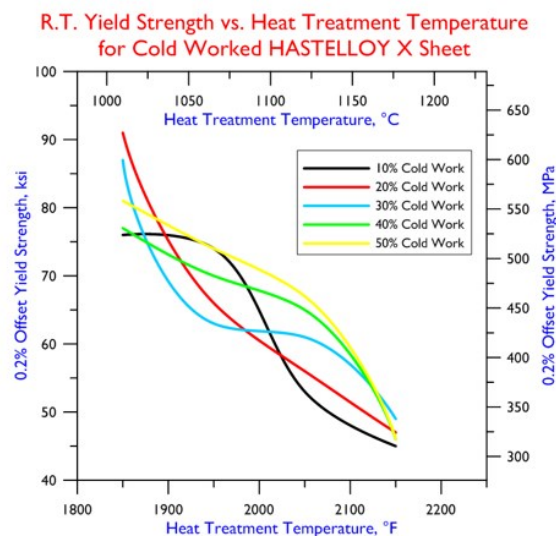
30	No Heat Treatment		142	979	169	1165	10	35 HRC
40	No Heat Treatment		159	1096	186	1282	8	37 HRC
50	No Heat Treatment		171	1179	200	1379	7	39 HRC
10	1850	1010	76	524	125	862	32	98 HRB
20	1850	1010	91	627	132	910	27	23 HRC
30	1850	1010	87	600	135	931	28	99 HRB
40	1850	1010	77	531	133	917	32	98 HRB
50	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), 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), 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, 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), hold at 1150°F for 8 hours, air cool
R-41	1	16 hours at 1400°F (760°C), air cool
WASPALLOY	3	2 hours at 1825°F (996°C), air cool, followed by 4 hours at 1550°F (843°C), air cool, 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), 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 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.