

# Heat Treatment for Special Alloy Fasteners

# Why Use Specialty Fasteners?

Critical applications (Fig. 1) require the use of materials whose performance envelope encompasses both normal duty and extreme duty demands. It is the latter that differentiates specialty fasteners and components from standard ones.



Figure 1'. Critical Performance Application Demanding Exotic Fastener Alloys – Jet Engines (photograph courtesy of Performance Review Institute)

# What Are Specialty

#### **Fasteners?**

Specialty fasteners are those whose applications demand performance over cost. Mechanical, physical and metallurgical properties are more stringent than those involving standard fasteners. Examples of equipment and industries that rely on specialty fasteners include power generation (e.g., gas turbines, offshore performance platforms), pulp and paper mills and electronic devices.

In aerospace (aircraft, rotorcraft, space) applications specialty fasteners are used on exteriors, interiors, avionics and flight systems (e.g., landing gear). Product examples include captive screws, rivets, gas springs, clamshell flexible couplings, quick release pins, tension latches, and telescopic slides. In automotive (motor sports, cars, off-road, heavy truck) fasteners and clamping device are commonplace throughout, including the engine, body and subsystems.

### **Alloy Fastener Materials**

There are some unique material selection challenges in the design of very-high-strength / high performance fasteners. These types of fasteners are often exposed to high stress concentration in the thread roots (caused by the tensile stresses produced from extremely high clamping loads) on top of which are superimposed any fatigue loads. To meet these challenges, the designer often selects alloys often classified as "exotic", primarily due to their chemistry and ability to perform at elevated temperatures (**Table 1**).

Class	Alloy	Examples
0	Steels <sup>a</sup>	A286
1A	Stainless Steels <sup>b</sup> Alloy 20, Alloy 50, Alloy 60, Custom 450, Carpenter 21, Carpenter CB3, 904L, AL6XN, Avesta 254SMo	
1B	Stainless Steels <sup>a</sup>	13-8, 17-4, 17-7
1C	Stainless Steels °	2304, 2205, 2507, 2707, 3207, Ferralium 255-SD50
1D	Stainless Steels <sup>d</sup>	50, 60
2A	Superalloys <sup>e</sup>	B, C-276, C-2000, C-22, C-4, G, X
2B	Superalloys <sup>f</sup>	230, HR120, HR160, ULTIMET 1233
2C	Superalloys <sup>9</sup>	600, 601, 615, 718, 800/800H, 825, 925, X750, 25-6Mo
2D	Superalloys <sup>h</sup>	Waspaloy
ЗA	Nickel Alloys	B2, B3, G30
3B	Monel	400, 405, 500
4	Other	Co, Ta, Ti, Zr

Notes: [a] Precipitation hardening grades / [b] Chromium-Nickel-Molybdenum grades (with selected alloy additions) / [c] Duplex & Super Duplex grades / [d] Nictronic alloys / [e] Hastalloy grades / [f] Haynes International alloys / [g] Inconel grades / [h] Other superalloy grades

## **Alloy Chemistry**

The chemistry of exotic alloys **(Table 2A – 2C)** is one of uniqueness brought about in order to address a specific application niche.

Element	Alloy 20(%)	Alloy 50(%)	Custom 450(%)	AL6XN(%)	17-4(%)	17-7(%)	904L(%)
Fe	-	-	[c]	[c]	-	[c]	[c]
Ni	32 - 35	11.5 – 13.5	5 - 7	23.5 - 25.5	3 - 5	6.5 - 7.75	23 - 28
Cr	19 - 21	20.5 - 23.5	14 – 16	20 - 22	15 - 17.5	16 - 18	19 – 23
Мо	2 - 3	1.5 - 3	0.50 – 1.0	6 - 7	-	-	4 - 5
Mn	2.0 <sup>b</sup>	4 - 6	1.0 <sup>b</sup>	2.0 <sup>b</sup>	1.0 <sup>b</sup>	1 <sup>b</sup>	2.0 b
Si	1.0 <sup>b</sup>	1.0 <sup>b</sup>	1.0 <sup>b</sup>	1.0 <sup>b</sup>	1.0 <sup>b</sup>	1.0 <sup>b</sup>	1.0 <sup>b</sup>
Ν	-	0.20 - 0.40		0.18 - 0.25	-	-	-
Al	-	-		-	-	0.75 - 1.5	-
С	0.060 b	0.060 <sup>b</sup>	0.050 <sup>b</sup>	0.030 b	0.07 <sup>b</sup>	0.09 <sup>b</sup>	0.02 <sup>b</sup>
S	0.035 <sup>b</sup>	0.010 <sup>b</sup>	0.030 <sup>b</sup>	0.03 <sup>b</sup>	0.030 b	0.040 <sup>b</sup>	0.035 <sup>b</sup>
Cu	3 - 4	-	1.25 – 1.75	0.75 <sup>b</sup>	3 - 5	-	1 – 2
Nb	-	0.10 - 0.30	-	-	-	-	-
Р	0.035 <sup>b</sup>	0.040 <sup>b</sup>	0.030 <sup>b</sup>	0.04 <sup>b</sup>	0.040 <sup>b</sup>	0.040 <sup>b</sup>	0.045 <sup>b</sup>
V	-	0.10 - 0.30	-	-	-	-	-
Cb + Ta	[d]	-	-	-	0.15 - 0.45	-	-

Table 2A. Select Class 1 – Nominal Alloy Chemistries

Notes: [a] Minimum / [b] Maximum / [c] Balance / [d] Columbium + Tantalum added (8.0 x C% to 1.0%) http://www.rolledalloys.com/alloys/nickel-alloys/alloy-20/en/



#### Table 2B.

Select Class 2 – Nominal Alloy Chemistries

Element	HR-120 (%)	HR-160 (%)	Inconel 600(%)	Inconel 718(%)	Inconel 925(%)	C276 (%)
Fe	33 <sup>b</sup>	2 <sup>b</sup>	6 - 10	[c]	22ª	4.0 - 7.0
Ni	37	37 <sup>c</sup>	72ª	50 - 55	42 - 46	55.0
Со	3 °	29		1.00 <sup>b</sup>	-	2.5 <sup>b</sup>
Cr	25	28	14 - 17	17 – 21	19.5 - 22.5	14.5 - 16.5
Мо	2.5 °	1 <sup>c</sup>	-	2.8 - 3.3	2.5 - 3.5	15 – 17
W	2.5 °	1 <sup>c</sup>	-	-	-	3.0 - 4.5
Cb	0.7	1 <sup>c</sup>	-	-	-	-
Mn	0.7	0.50	1.0 <sup>b</sup>	0.35 <sup>b</sup>	1.0 <sup>b</sup>	1.0 <sup>b</sup>
Si	0.6	2.75	0.5 <sup>b</sup>	0.35 <sup>b</sup>	0.5 <sup>b</sup>	0.08 <sup>b</sup>
Ν	0.20	-	-		-	-
Al	0.1	-	-	0.20 - 0.80	0.1 – 0.5	-
С	0.05	0.05	0.15 <sup>b</sup>	0.08 <sup>b</sup>	0.03 <sup>b</sup>	0.010 <sup>b</sup>
В	0.004	-	-	0.006 <sup>b</sup>	-	-
Ti	-	0.5	-	0.65 - 1.15	1.9 – 2.4	-
S	-	-	0.015 <sup>b</sup>	0.015 <sup>b</sup>	0.030 <sup>b</sup>	0.030 <sup>b</sup>
Cu	-	-	0.50 <sup>b</sup>	0.30 <sup>b</sup>	1.5 – 3.0	-
Nb	-	-	-	4.75 - 5.50	0.5 <sup>b</sup>	-
Р	-	-	-	0.015 <sup>b</sup>	-	0.04 <sup>b</sup>
V	-	-	-	-	-	0.35 <sup>b</sup>

Table 2C.
Select Class 3 – Nominal Alloy Chemistries

-	FI DOMAN DOMAN Monel Monel					
Element	B2(%)	B3(%)	G30(%)	400 (%)	K500 (%)	
Fe	2.0 <sup>b</sup>	1.0 - 3.0	13 – 17	2.5 b	2.0 b	
Ni	[c]	65ª	[c]	63.0ª	63 - 70	
Со	1.0 <sup>b</sup>	3.0 <sup>b</sup>	5.0 <sup>b</sup>	-	-	
Cr	1.0 <sup>b</sup>	1.0 -3.0	28 - 31.5	-	-	
Мо	26 - 30	27 - 32	4 - 6	-	-	
W	-	3.0 <sup>b</sup>	1.5 - 4.0	-	-	
Mn	1.0 <sup>b</sup>	-	1.5 <sup>b</sup>	2.0 <sup>b</sup>	1.5 <sup>b</sup>	
Si	0.010 <sup>b</sup>	0.10 <sup>b</sup>	0.80 <sup>b</sup>	0.5 <sup>b</sup>	0.50 <sup>b</sup>	
Al	-	0.50 <sup>b</sup>	-	-	2.30 - 3.15	
С	0.02 <sup>b</sup>	0.010 <sup>b</sup>	0.030 <sup>b</sup>	0.30 <sup>b</sup>	0.25 <sup>b</sup>	
Ti	-	0.20 b	-	-	0.35 – 0.85	
S	0.030 <sup>b</sup>	-	0.020 <sup>b</sup>	0.024 <sup>b</sup>	0.010 <sup>b</sup>	
Cu	-	0.20 b	1.0 - 2.4	28 - 34	[c]	
Ρ	0.040 <sup>b</sup>	-	0.04 <sup>b</sup>	-	-	

Notes: [a] Minimum / [b] Maximum / [c] Balance

#### **Heat Treatment**

The heat treatment of specialty fasteners (Table **4**) is intended to enhance their properties (metallurgical, mechanical, physical) and maximize their in service performance. This requires accurate control of process and equipment induced variability including repeatability of times, temperatures, and furnace atmospheres. A variety of different types of equipment can be used; both batch styles are popular depending on production demand.



Figure 2. Shaker Hearth Furnace for the Heat Treatment of Titanium Fasteners (front end) (courtesy of DF Industries)

Notes: [a] Minimum / [b] Maximum / [c] Balance



Figure 3. Shaker Hearth Furnace for the Heat Treatment of Titanium Fasteners (rear end) (courtesy of DF Industries)

Alloy	Heat Treatment
A286	For high stress rupture strength: Solution treat at 980°C (1800°F) for one (1) hour, rapid cool, age at 720°C (1325°F) for 16 hours, air cool. <sup>a</sup> For high room temperature tensile strength and stress rupture ductility: Solution treat at 900°C (1650°F) for two (2) hours, rapid cool, age at 720°C (1325°F) for 16 hours, air cool. <sup>b</sup>
Avesta 2205	Solution anneal at 1020°C - 1100°C (1870°F - 2010°F) followed by water quench. <sup>c,d</sup>
HR-120 e	Normally supplied in the solution annealed condition, unless otherwise specified. Solution annealed at 1175°C - 1230°C (2150°F - 2250°F) and rapidly cooled. <sup>f</sup>
HR-160 e	Normally supplied in the solution annealed condition, unless otherwise specified. Solution annealed at 1120°C (2050°F) and rapidly cooled for optimum properties. Intermediate annealing, if required during fabrication and forming operations, can be performed at temperatures as low as 1065°C (1950°F).
230 e	Normally supplied in the solution heat-treated. Solution heat-treated in the range of 1175°C - 1245°C (2150°F - 2275°F) followed by rapidly cooling or water-quenched for optimum properties. <sup>9</sup>

Table 4. Heat Treatments for Exotic Fastener Alloys



Ferrature 25:5000         Solution heat treat a 100°C (1960°F) followed by an adjuganch, preliability in water, <sup>10</sup> A stress reliable heat temperature (allowed by air coult)           Daplax Alloy 2006         Anneal at 100°C (1960°F), followed by rapid cooling, ideality by water quanching:           Outputs Alloy 2007         Anneal at 100°C (1960°F), followed by rapid cooling by rapid acrowater quanching:           Super Duplex Alloy 2007         Solution anneal at a minimum of 100°C (1960°F) followed by rapid cooling by rapid acrowater quanching:           Open Duplex Alloy 2007         Solution anneal at 100°C - 1140°C (1960°F) followed by rapid cooling by rapid acrowater quanching:           Open Duplex Alloy 2007         Anneal at 100°C - 1140°C (1960°F) followed by rapid cooling, usually in water, plus precipitation preducing a coarse grait atrustime. Anneal at 100°C - 1100°C (1900°F), biol cooling, usually in water, plus precipitation hardening at 70°C (1960°F) for 8 hours, furnace cool to 20°C (1900°F), hold for a total apin grain of 120° hours, followed by air cooling.           Open Extra 100 Cooling 1100°C - 1140°C - 100°C (1900°F) followed by rapid cooling, usually in water, plus precipitation hardening at 70°C (1960°F) for 8 hours, furnace cool to 20°C (1900°F), hold for a total apin grain of 120°C protopen to 20°C (1900°F).           Inscrete 1718         Hardened by cool work only, Anneal at 955°C (1750°F) with rapid air cool. 20°C protopen to 20°C (1900°F).           Inscrete 200         Solution anneal at 100°C (1900°F - 1750°F) and a dirio to leasy 12 hours to air cooling.           Inscrete 200         Solutin nameal at 100°C (1900°F - 1750°F) and a dirio to	Alloy	Heat Treatment
Buptex Allay 2304         Anneal at 980°C (1900°F) followed by rapid acoding to prevent the precipitation of undesirable phases. <sup>14</sup> Super Duplex Allay 2307         Solution anneal at 0.00°C - 1140°C (1905°F - 2005°F) followed by rapid acoding in all, protective atmosphere or water.           Hyper Duplex Allay 300         Solution anneal at 0.00°C - 1140°C (1905°F - 2005°F) followed by rapid cooling in all, protective atmosphere or water.           Incent 600         Anneal at 0.00°C - 1150°C (2005°F - 2007°F) for 1 - 2 hours to obtain maximum creep and rupture strength.           Two hoets treatments are commonly used:         -Solution anneal at 102°C - 100°C (100°F - 1850°C (100°F) for 1 - 2 hours to obtain maximum creep and rupture strength.           Incent 718         Two hoets treatments are commonly used:         -Solution anneal at 122°C (120°F) for 8 hours, nece costs 0.25°C (1150°F) hold for a total aging time of 18 hours, followed by ar colling, *           Incent 825         Hardened by cold work only. Anneal at 95°C (170°F) with rapid are coll. *           Incent 925         Solution anneal at 92°C (110°F) - 110°F) for 10° totain tage training at 73°C (1130°F) for 8 hours, furnace coll at 40°C (190°F - 110°F) for 8 hours, furnace coll at 40°C (190°F) - 110°F) for 10° totain tage training at 73°C (1130°F) for 8 hours, furnace coll at 40°C (190°F) for 10°F) for 10°F hours, furnace coll at 40°C (190°F) for 10°F) for 10°F hours, furnace coll at 40°C (190°F) for 10°F) for 10°F hours, furnace coll at 40°C (190°F) for 10°F) for 10°F hours, furnace coll at 40°C (190°F) for 10°F) for 10°F hours, furnace coll at 40°C (190°F) for 10°F) for 10°F hours, furnace coll at 40°C (190°F) for 10°F) for 10°F hours, furnace col	Ferralium 255-SD50	treatment, when required, should be carried out by heating to 350°C (660°F), holding for two (2) hours at
Super Duplex Alloy 2007         Solution anneal at a minimum of 1050C [1925°F] followed by rapid colling in air, protective atmosphere or water.           Hyper Duplex Alloy 2007         Solution anneal at 100/0°C - 110/0°F 100/0°F - 2003°F) followed by rapid colling in air, protective atmosphere or water.           Incomel 400         Anneal at 100/0°C - 110/0°F 100/1°F - 2003°F) followed by rapid colling in air, protective atmosphere or water.           Incomel 400         Protect at 100/0°C - 110/0°F - 100/1°F 100/1°F - 2003°F) followed by rapid colling, usually in water, plus precipitation hardening at 720°C (1220°F) for 8 hours, furnace cool to 620°C (1100°F), hold for a total aging time of 18 hours, followed by air colling.           Incomel 718         Solution anneal at 90°C (1800°F - 1000°F) for 100°F - 180°F 1010°F), hold for a total aging time of 20 hours, formace cool to 620°C (1200°F), hold for a total aging time of 20 hours, followed by air colling.           Incomel 725         Hardened by air cooling.         Solution anneal at 90°C (1800°F   and air cool. Aging at 720°C (1150°F) for 8 hours, furnace cool at 40°C (75°F) per hour to 625°C (1170°F) and air cool. Aging at 720°C (1920°F) for 8 hours, furnace cool at 40°C (75°F) per hour to 625°C (1170°F), and air cool.           Hastelloy C276         Normally furnished in the solution heat-treated condition. Solution treat at 1040°C - 1150°C [1900°F - 2100°F] and allowed by rapid air-cooling or water quenching.*           Hastelloy C-4         Solution anneal at 91°C (180°F) indiced by rapid air-cooling or water quenching.*           Hastelloy C-4         Solution heat treatment consists at 1180°C [2150°F] followed by rapid air-cooli	Duplex Alloy 2205	Anneal at 1040°C (1900°F), followed by rapid cooling, ideally by water quenching. <sup>j</sup>
Hyper Duplex Alloy 3007         Solution anneal at 1040°C - 1140°C (1909°F - 2085°F) followed by rapid cooling in air, protective atmosphere or water.           Inconel 400         Anneal at 1010°C (1500°F) for 15 minutes. Briel exposure to 1040°C (1900°F) will give soft material without producing a coarse grain structure. Anneal at 109°C - 1150°C (200°F) (or 1 - 2 hours to obtain maximum creep and rupture strength."           Inconel 718         Two heat Instituents are commonly used:         Solution anneal at 025°C - 100°C (1900°F) - 1850°F] followed by rapid cooling, usually in water, plus precipitation hardening at 720°C (130°F) for 5 hours, furnace cool to 650°C (1000°F), hold for a total aging time of 18 hours, followed by ar cooling, "           Inconel 718         Hardened by cold work only. Anneal at 955°C (1700°F) and air cool. Aging at 720°C (130°F) for 8 hours, furnace cool to 650°C (1200°F), hold for a total aging time of 20 hours, followed by ar cooling, "           Inconel 725         Solution anneal at 960°C (1160°F) - 100°F) and air cool. Aging at 720°C (130°F) for 8 hours, furnace coal at 40°C (75°F) per hear to 635°C (1700°F) and air cool. Aging at 720°C (1500°F) evalues then air cool.           Hastelloy 620         Normally furnished in the solution heat-treated condition. Solution treat at 1040°C (1900°F - 200°F) and rapid air-cooling or water quenching. "           Hastelloy 620         Solution heat treatment consists at 1080°C (1500°F) and rapid air-cooling or water quenching. "           Hastelloy 624         Solution heat treatment consists at 1080°C (1500°F).           Moreal at 870°C - 870°C (1600°F - 1600°F). Cooling rate not critical. Theorine at 540-50°F. Stres arelief of	Duplex Alloy 2304	
HyperDudgex Adoy 2027         water.           Inconet 600         Annext at 1010°C (1550°F) for 15 minutes. Brief coposure to 1640°C (190°F) will give soft material without producing a coarse grain structure. Annext at 100°°C - 110°C (200°F) - 210°F) for 1 - 2 hours to obtain maximum creep and rugburs strength.           Inconet 718         Foot heat treatments are commonly used:         ••olution anneal at 92°C - 1010°C (1100°F - 1650°F) followed by rapid cooling, usually in water, plus precipitation hardening at 72°C (1250°F) for 10 hours, furnace cool to 62°C (1100°F), hold for a total aging time of 18 hours, formace cool to 62°C (1200°F), hold for a total aging time of 20 hours, followed by are cooling.           Inconet 825         Hordened by cold work only. Anneat at 95°C (1170°F) with rapid air cool.         **           Inconet 825         Hordened by cold work only. Anneat at 95°C (1170°F) with rapid air cool.         **           Inconet 826         Hordened by cold work only. Anneat at 95°C (1170°F) with rapid air cool.         *           Inconet 826         Normally furnished in the soluton heat-treated condition. Solution treat at 104°°C (190°F - 210°F) and rapid guench.*           Hastelloy 027         Normally furnished in the soluton heat-treated condition. Solution treat at 106°C (190°F) and rapid guench.*           Hastelloy 02.000         Solution heat treatment consists at 1180°C (210°F) followed by rapid air-cooling or water quenching.*           Hastelloy 02.000         Solution heat treatment at 300°C (100°F - 180°F).         Solution heat reatmatin at soluton front and rapid quench.*	Super Duplex Alloy 2507	Solution anneal at a minimum of 1050C (1925°F) following by rapid air or water quench. <sup>I, m</sup>
Inconel 400 producing a cararse grain structure. Annual at 1090°C - 1150°C (2000° - 2100°F) for 1 - 2 hours to obtain maximum creep and rupture strength." Two heat treatments are commonly used:Solution annual at 225°C - 1010°C (1700°F - 1800°F) followed by rapid cooling, usually in water, plus precipitation hardening at 720°C (1200°F) followed by rapid cooling, usually in water, plus precipitation hardening at 720°C (1400°F) for 10 hours, furnace cool to 620°C (1200°F), hold for a total aging time of 20 hours, totlowed by are coolingSolution annual at 1040°C - 1055°C (1700°F - 1070°F) and hold for a total aging time of 20 hours, totlowed by are coolingSolution annual at 920°C (1800°F) for 10 hours, furnace cool to 650°C (1200°F), hold for a total aging time of 20 hours, totlowed by are coolingSolution annual at 920°C (1800°F) and hold for at cast 12 hours then air cool. *' Inconel 825 Hardened by cold work only. Anneel at 955°C 11750°F] with rapid air cool. *' Inconel 825 Hastellay C276 Normally furnished in the solution heat-treated condition. Solution treat at 1040°C - 1150°C (1900°F - 2100°F) and rapid ycooled.* Hastellay C30 Solution heat treatment consists at 1180°C (2150°F) followed by rapid air-cooling or water quenching.* Hastellay C 4 Solution heat treatment consists at 1180°C (2150°F) followed by rapid air-cooling or water quenching.* Hastellay C 4 Anneel at 870°C - 980°C (11400°F - 1800°F), cooling rate not critical.* Stress relief, if equired, is at 540-570°C. Stress relief of cold worked material at 300°C 960°C (1400°F - 1800°F).* Monel 405 This ality can be anneeled at 870°C - 980°C (1400°F - 1800°F), cooling rate not critical. Otherwise this alloy does not respond to heat treating. Anneel in the range of 780°C = 870°C (1400°F - 1800°F), cooling rate not critical. Otherwise this alloy does not respond to heat rested in 250°C 500°C. Intervise this alloy does not respond to heat rested in 250°C 500°C (1400°F - 1600°F).* Monel 405 Monel 405 Monel 405 Monel 405 Monel 405 Monel 405 Monel	Hyper Duplex Alloy 3207	
+Solution anneal at 225°C 1010°C 11700°F - 1800°F) followed by rapid cooling, usualty in water, plus precipitation hardening at 720°C (1325°F) for 8 hours, furnace cool to 620°C (1150°F), hold for a total aging time of 18 hours, followed by air cooling, -Solution anneal at 1040°C - 1065°C 1000-150°F] followed by rapid cooling, usualty in water, plus precipitation hardening at 780°C (1100°F - 1000°F) and air cool. 450°C (1120°F), hold for a total aging time of 20 hours, followed by air cooling, *         Inconel 825       Hardened by cold work only. Anneal at 955°C (11750°F) with rapid air cool. *'         Inconel 926       Solution anneal at 980°C (1180°F - 1900°F) and air cool. Aging at 730°C (1150°F) for 8 hours, furnace cool at 40°C (75°F) per hour to 635°C (1175°F) and hold for at least 12 hours then air cool.         Hastelloy C276       Rapidy coaled.*         Hastelloy G30       Solution anneal at 1180°C (2150°F) followed by rapid air-cooling or water quenching.*         Hastelloy C-240       Solution heat treatment consists at 1180°C (2150°F) followed by rapid air-cooling or water quenching.*         Hastelloy C-240       Solution heat treat at 1064°C (150°F).         Monel 400       Anneal at 173°C (275°F) followed by rapid air-cooling or water quenching.*         Hastelloy C-240       Solution heat read at 036°C (1500°F.1 and rapid guench.         Monel 400       Anneal at 75°C - 980°C (1400°F - 1800°F), cooling rate not critical. Stress relief, if required, is at 540-570°C.         Stress relief of cold worked material 4300°C (1510°F.1       Solution heat read at 300°C (1510°F.1         Monel 405	Inconel 600	producing a coarse grain structure. Anneal at 1090°C - 1150°C (2000° - 2100°F) for 1 – 2 hours to obtain maximum
Incomel 925         Solution anneal at 980°C 11800°F - 1900°F1 and air cool. Aging at 730°C (1350°F1 for 8 hours, furnace cool at 40°C (75°F1 per hour to 635°C (1175°F1) and hold for at least 12 hours then air cool.           Hastelloy C276         Normally furnished in the solution heat-treated condition. Solution treat at 1040°C -1150°C (1900°F - 2100°F1) and rapid y cooled.           Hastelloy C30         Solution heat treatment consists at 1180°C (2150°F1 followed by rapid air-cooling or water quenching."           Hastelloy C-2000         Solution heat treatment consists at 1180°C (2150°F1 followed by rapid air-cooling or water quenching."           Hastelloy C-2000         Solution heat treatment consists at 1180°C (2150°F1 followed by rapid air-cooling or water quenching."           Hastelloy C-4         Solution heat treatment consists at 1180°C (2150°F1, coling rate not critical." Stress relief, if required, is at 540-570°C. Stress relief of cold worked material at 300°C (510°F1, '           Monel 400         Anneal at 870°C - 980°C (1400°F - 1800°F1, cooling rate not critical." Otherwise this alloy dees not respond to heat treating.           Monel 405         This alloy can be annealed at 870°C - 980°C (1400°F - 1400°F1, 'Alternatively, anneal at 980°C (1800°F1 for hot-finished products and 1040°C (1900°F1 for cold-drawn products for optimum response to subsequent age hardening.'           Monel 4500         The following age-hardening procedures are recommended for achievement of maximum properties ":           A. Soft material 1140-180 Brinell, 75-90 RBI. Hold for 16 hours at 590°C - 410°C (1100°F - 1125°F Followed by furnace or air cooling, or by quenching, without	Inconel 718	<ul> <li>Solution anneal at 925°C - 1010°C (1700°F - 1850°F) followed by rapid cooling, usually in water, plus precipitation hardening at 720°C (1325°F) for 8 hours, furnace cool to 620°C (1150°F), hold for a total aging time of 18 hours, followed by air cooling.</li> <li>Solution anneal at 1040°C - 1065°C (1900-1950°F) followed by rapid cooling, usually in water, plus precipitation hardening at 760°C (1400°F) for 10 hours, furnace cool to 650°C (1200°F), hold for a total aging time of 20 hours,</li> </ul>
Incone 1/25       [75°F] per hour to 635°C [1175°F] and hold for at least 12 hours then air cool.         Hastelloy C276       Normally furnished in the solution heat-treated condition. Solution treat at 1040°C - 1150°C [1900°F - 2100°F] and rapid y cooled. *         Hastelloy G30       Solution heat treatment consists at 1180°C [2150°F] followed by rapid air-cooling or water quenching. *         Hastelloy C-2000       Solution heat treat at 1066°C [1950°F] and rapid quench.         Mastelloy C-4       Solution heat treat at 1066°C [1950°F] and rapid quench.         Monel 400       Anneal at 870°C -980°C [1600°F - 1800°F], cooling rate not critical.* Stress relief, if required, is at 540-570°C. Stress relief of cold worked material at 300°C [510°F].*         Monel 405       This alloy can be annealed at 870°C -980°C [1600°F - 1800°F], cooling rate not critical. Otherwise this alloy does not respond to heat treating.         Anneal in the range of 750°C - 870°C [1600°F - 1800°F]. * Alternatively, anneal at 980°C [1800°F] for hot-finished products and 1040°C [1900°F] for cold-drawn products for optimum response to subsequent age hardening.*         The following age-hardening procedures are recommended for achievement of maximum properties *: A. Soft material 1140-180 Brinell, 75-90 RBI. Hold for 16 hours at 590°C - 610°C (1100°F - 1125°F followed by coling for 900°F to room temperature may be carried out by furnace or air cooling, or by quenching. #the arterial at 100 to 1125°F, followed by cooling to 900°F to a solut espender to 125°F per hour to 480°C (190°F] for 2010°F and resp.**         A. Soft material [140-180 Brinell, 75-90 RBI. Hold for 16 hours at tegen 40°C (1150°F for 50°F) per	Inconel 825	Hardened by cold work only. Anneal at 955°C (1750°F) with rapid air cool. <sup>q, r</sup>
Hastelloy G276       rapidly cooled.*         Hastelloy G30       Normally furnished in the solution heat-treated condition. Solution treat at 1065°C [1950°F] and rapid quench.*         Hastelloy G30       Solution heat treatment consists at 1180°C [2150°F] followed by rapid air-cooling or water quenching.*         Hastelloy C-2000       Solution neat at 1135°C [2075°F] followed by rapid air-cooling or water quenching.*         Hastelloy C-4       Solution heat treat at 1066°C [1950°F] and rapid quench.         Monel 400       Anneal at 870°C - 980°C [1600°F - 1800°F], cooling rate not critical.* Stress relief, if required, is at 540-570°C.         Stress relief of cold worked material at 300°C [510°F].*       Monel 405         Monel 405       This alloy can be annealed at 870°C - 980°C [1600°F - 1800°F], cooling rate not critical. Otherwise this alloy does not respond to heat treating.         Anneal in the range of 750°C - 870°C [1400°F - 1400°F], * Alternatively, anneal at 980°C [1800°F] for hot-finished products and 1040°C (1900°F] for cold-drawn products for optimum response to subsequent age hardening.*         The following age-hardening procedures are recommended for achievement of maximum properties **:       A. Soft material (140-180 Brinell, 75-90 RPB). Hold for 16 hours at 590°C - 610°C [1100°F - 1125°] Followed by furnace cooling at the rate of 15 to 25°F per hour to 480°C (900°F]. Cooling fram 900°F to room temperature may be carried out by furnace or air cooling, or by quenching, without regard for cooling rate. **         Monel K500       B. Moderately cold-worked material (126-320 Brinell, 55-35 RC]. Hold for 8 hours oro	Inconel 925	
Hastelloy G30         Solution heat treatment consists at 1180°C (2150°F) followed by rapid air-cooling or water quenching. "           Hastelloy C-2000         Solution anneal at 1135°C (2075°F) followed by rapid air-cooling or water quenching. "           Hastelloy C-4         Solution heat treat at 1066°C (1950°F) and rapid quench.           Monel 400         Anneal at 870°C -980°C (1600°F - 1800°F), cooling rate not critical." Stress relief, if required, is at 540-570°C. Stress relief of cold worked material at 300°C (510°F). *           Monel 405         This alloy can be annealed at 870°C -980°C (1400°F - 1800°F), cooling rate not critical. Otherwise this alloy does not respond to heat treating.           Monel 405         Anneal in the range of 750°C - 870°C (1400°F - 1600°F), * Alternatively, anneal at 980°C (1800°F) for hot-finished products and 1040°C (1900°F) for cold-drawn products for optimum response to subsequent age hardening.*           Monel K500         Anneal in the range of 15 to 25°F per hour to 480°C (190°F). Cooling from 900°F to room temperature may be carried out by furnace or air cooling, or by quenching, without regard for cooling rate. **           B. Moderately cold-worked material (175-250 Brinell, 8-25 RBI). Hold for 8 hours or longer at 1100 to 1125°F, followed by cooling to 900°F at a rate not to exceed 8°C - 14°C (15°F - 25°F) per hour. Higher hardness can be obtained by holding for as long as 16 hours at temperature, particularly if the material has been cold-worked only slightly. As a general rule, material with an initial hardness in 75-200 Brinell should be held the full 16 hrs. Material close to the top end (250 Brinell, 25-35 Rcl, Hold for 6 hours or longer at 525C - 540C (180F - 1000°F) followed by cooling	Hastelloy C276	
Hastelloy C-2000       Solution anneal at 1135°C (2075°F) followed by rapid air-cooling or water quenching. *         Hastelloy C-4       Solution heat treat at 1066°C (1950°F) and rapid quench.         Monel 400       Anneal at 870°C -980°C (1600°F - 1800°F), cooling rate not critical. * Stress relief, if required, is at 540-570°C. Stress relief of cold worked material at 300°C (1600°F - 1800°F), cooling rate not critical. Otherwise this alloy cose not respond to heat treating.         Monel 405       This alloy can be annealed at 870°C - 980°C (1400°F - 1800°F), cooling rate not critical. Otherwise this alloy does not respond to heat treating.         Anneal in the range of 750°C - 870°C (1400°F - 1600°F). * Alternatively, anneal at 980°C (1800°F) for hot-finished products and 1040°C (1900°F) for cold-drawn products for optimum response to subsequent age hardening.*         Monel K500       Anneal in the range of 750°C - 870°C per per hour to 480°C (1900°F). Cooling from 900°F to room temperature may be carried out by furnace or air cooling, or by quenching, without regard for cooling rate. **         Monel K500       B. Moderately cold-worked material (175-250 Brinell, 8-25 RB). Hold for 8 hours or longer at 1100 to 1125°F, followed by cooling to 900°F at a rate not to exceed 8°C - 14°C (15°F - 25°F) per hour. Higher hardness can be obtained by holding for as long as 16 hours at thereital has been cold-worked only slightly. As a general rule, material with an initial hardness of 175-200 Brinell should be held the full 16 hrs. Material close to the top end (250 Brinell or 25 HRcl, Hold for 6 hours or longer at 52C - 540C (1806°F - 1000°F) followed by cooling to 480°C (190°°F) at rate not exceeding 8°C - 14°C (15°F - 25°F) per hour. **         904L	Hastelloy B3	Normally furnished in the solution heat-treated condition. Solution treat at 1065°C (1950°F) and rapid quench. <sup>t</sup>
Hastelloy C-4       Solution heat treat at 1066°C (1950°F) and rapid quench.         Monel 400       Anneal at 870°C -980°C (1600°F - 1800°F), cooling rate not critical." Stress relief, if required, is at 540-570°C.         Stress relief of cold worked material at 300°C (510°F).*       This allay can be annealed at 870°C -980°C (1600°F - 1800°F), cooling rate not critical. Otherwise this allay does not respond to heat treating.         Monel 405       This allay can be annealed at 870°C -980°C (1400°F - 1600°F).* Alternatively, anneal at 980°C (1800°F) for hot-finished products and 1040°C (1900°F) for cold-drawn products for optimum response to subsequent age hardening.*         Monel K500       Anneal in the range of 750°C - 870°C (1400°F -1600°F).* Alternatively, anneal at 980°C (1800°F) for hot-finished products and 1040°C (1900°F) for cold-drawn products for optimum response to subsequent age hardening.*         Monel K500       B. Moderately cold-new Brinell, 75-90 RBJ. Hold for 16 hours at 590°C - 610°C (1100°F - 1125°) F followed by furnace cooling at the rate of 15 to 25°F per hour to 480°C (900°F). Cooling from 900°F to room temperature may be carried out by furnace or air cooling, or by quenching, without regard for cooling rate. **         B. Moderately cold-worked material (175-250 Brinell, 8-25 RB). Hold for 8 hours or longer at 1100 to 1125°F, followed by cooling to 900°F at a rate not to exceed 8°C - 14°C (15°F - 25°F] per hour. Higher hardness can be obtained by holding for as long as 16 hours at temperature, particularly if the material has been cold-worked only slightly. As a general rule, material with an initial hardness of 175-200 Brinell should be held the full 16 hrs. Material Cose to the top end (250 Brinell, 25-35 RC). Hold for 6 hours or longer at 2	Hastelloy G30	Solution heat treatment consists at 1180°C (2150°F) followed by rapid air-cooling or water quenching. "
Monel 400       Anneal at 870°C - 980°C (1400°F - 1800°F), cooling rate not critical." Stress relief, if required, is at 540-570°C.         Monel 400       This alloy can be annealed at 870°C - 980°C (1600°F). *         This alloy can be annealed at 870°C - 980°C (1600°F). *       This alloy can be annealed at 870°C - 980°C (1400°F - 1800°F), cooling rate not critical. Otherwise this alloy does not respond to heat treating.         Anneal in the range of 750°C - 870°C (1400°F - 1600°F). * Alternatively, anneal at 980°C (1800°F) for hot-finished products and 1040°C (1900°F) for cold-drawn products for optimum response to subsequent age hardening.*         The following age-hardening procedures are recommended for achievement of maximum properties <sup>16</sup> :       A. Soft material (140-180 Brinelt, 75-90 RB]. Hold for 16 hours at 590°C - 610°C (1100°F - 125°F) Followed by furnace cooling at the rate of 15 to 25°F per hour to 480°C (900°F). Cooling from 900°F to room temperature may be carried out by furnace or air cooling, or by quenching, without regard for cooling rate. <sup>11</sup> B. Moderately cold-worked material (175-250 Brinell, 8-25 RB). Hold for 8 hours or longer at 1100 to 1125°F, followed by cooling to 900°F at a rate not to exceed 8°C - 14°C (15°F - 25°F) per hour. Higher hardness can be obtained by holding for as long as 16 hours at temperature, particularly if the material has been cold-worked only slightly. As a general rule, material with an initial hardness of 175-200 Brinell should be held the full 16 hrs. Material close to the top end (250 Brinell, 25-35 Rc]. Hold for 6 hours or longer at 525C - 540C (980F - 1000°F) followed by cooling to 480°C (900°F) at a rate not exceeding 8°C - 14°C (15°F - 25°F) per hour. <sup>44</sup> 904L SS       Harden by solution heat-treat at 1	Hastelloy C-2000	Solution anneal at 1135°C (2075°F) followed by rapid air-cooling or water quenching. $^{ m v}$
Monel 400       Stress relief of cold worked material at 300°C [510°F]. *         Monel 405       This alloy can be annealed at 870°C -980°C [1600°F - 1800°F], cooling rate not critical. Otherwise this alloy does not respond to heat treating.         Anneal in the range of 750°C - 870°C (1400°F - 1600°F). * Alternatively, anneal at 980°C (1800°F] for hot-finished products and 1040°C (1900°F) for cold-drawn products for optimum response to subsequent age hardening.*         The following age-hardening procedures are recommended for achievement of maximum properties **:       A. Soft material (140-180 Brinell, 75-90 RB). Hold for 16 hours at 590°C - 610°C (1100°F - 1125°) F followed by furnace cooling at the rate of 15 to 25°F per hour to 480°C (900°F). Cooling from 900°F to room temperature may be carried out by furnace or air cooling, or by quenching, without regard for cooling rate. **         B. Moderately cold-worked material (175-250 Brinell, 8-25 RB). Hold for 8 hours or longer at 1100 to 1125°F, followed by cooling to 900°F at a rate not to exceed 8°C - 14°C (15°F - 25°F) per hour. Higher hardness can be obtained by holding for as long as 16 hours at temperature, particularly if the material hard be held the full 16 hrs. Material close to the top end (250 Brinell, 0-25 RC). Hold for 6 hours or longer at 525C - 540C (980F - 1000°F) followed by cooling to 480°C (900°F) at a rate not exceed 8°C - 14°C (15°F - 25°F) per hour. **         904L SS       Harden by solution heat-treat at 1090°C - 1175°C (1995°F - 2150°F) followed by rapid cooling.         Waspaloy       Heat treat in a three-step sequence (solution treatment, stabilization and age-harden).         A. For optimum high-temperature creep and stress-rupture properties:       - Solution tre	Hastelloy C-4	Solution heat treat at 1066°C (1950°F) and rapid quench.
Monet 405       not respond to heat treating.         Anneal in the range of 750°C - 870°C (1400°F - 1600°F). <sup>7</sup> Alternatively, anneal at 980°C (1800°F) for hot-finished products and 1040°C (1900°F) for cold-drawn products for optimum response to subsequent age hardening. <sup>7</sup> The following age-hardening procedures are recommended for achievement of maximum properties <sup>140</sup> :         A. Soft material (140-180 Brinell, 75-90 RB). Hold for 16 hours at 590°C - 610°C (1100°F - 1125°) F followed by furnace cooling at the rate of 15 to 25°F per hour to 480°C (900°F). Cooling from 900°F to room temperature may be carried out by furnace or air cooling, or by quenching, without regard for cooling rate. <sup>160</sup> B. Moderately cold-worked material (175-250 Brinell, 8-25 RB). Hold for 8 hours or longer at 1100 to 1125°F, followed by cooling to 900°F at a rate not to exceed 8°C - 14°C (15°F - 25°F) per hour. Higher hardness can be obtained by holding for as long as 16 hours at temperature, particularly if the material has been cold-worked only slightly. As a general rule, material with an initial hardness of 175-200 Brinell should be held the full 16 hrs. Material close to the top end [250 Brinell or 25 HRc], should attain full hardness in 8 hours. <sup>64</sup> 904L SS       Harden by solution heat-treat at 1090°C - 1175°C (1995°F - 2150°F) followed by rapid cooling.         Heat treat in a three-step sequence (solution treatment, stabilization and age-harden).       A. For optimum high-temperature creep and stress-rupture properties:         Solution treat at 1080°C (1975°F) for 24 hours followed by air cooling.       Age harden at 760°C (1400°F) for 16 hours followed by air cooling.         Boder 1000°C (190°C) I 10° 16 hours followed by air c	Monel 400	
Monel K500products and 1040°C (1900°F) for cold-drawn products for optimum response to subsequent age hardening. <sup>2</sup> Monel K500The following age-hardening procedures are recommended for achievement of maximum properties <sup>18</sup> : A. Soft material (140-180 Brinell, 75-90 RB). Hold for 16 hours at 590°C - 610°C (1100°F - 1125°) F followed by furnace cooling at the rate of 15 to 25°F per hour to 480°C (900°F). Cooling from 900°F to room temperature may be carried out by furnace or air cooling, or by quenching, without regard for cooling rate. <sup>16</sup> B. Moderately cold-worked material (175-250 Brinell, 8-25 RB). Hold for 8 hours or longer at 1100 to 1125°F, followed by cooling to 900°F at a rate not to exceed 8°C - 14°C (15°F - 25°F) per hour. Higher hardness can be obtained by holding for as long as 16 hours at temperature, particularly if the material has been cold-worked only slightly. As a general rule, material with an initial hardness of 175-200 Brinell should be held the full 16 hrs. Material close to the top end (250 Brinell or 25 HRc) should attain full hardness in 8 hours. <sup>64</sup> 904L SSHarden by solution heat-treat at 1090°C - 1175°C (1995°F - 2150°F) followed by rapid cooling.WaspaloyHeat treat in a three-step sequence (solution treatment, stabilization and age-harden). A. For optimum high-temperature creep and stress-rupture properties: - Solution treat at 1080°C (1975°F) for 4 hours followed by air cooling (anticipated hardness: 20-25 HRC). Stabilization by heating to 845°C (1550°F) for 24 hours followed by air cooling (articipated hardness: 20-25 HRC). B. For optimum moron- and high-temperature tensile properties: - Solution theat treat at 995-1035°C (1825-1895°F) for 4 hours followed by air cooling (articipated hardness: 20-25 HRC). B. For optimum moron- and high-temperature tensile properties: - Solution heat treat at 995-1035°C (1825-1895°F) for	Monel 405	
Heat treat in a three-step sequence (solution treatment, stabilization and age-harden).A. For optimum high-temperature creep and stress-rupture properties: - Solution treat at 1080°C (1975°F) for 4 hours followed by air cooling (anticipated hardness: 20-25 HRC). Stabilization by heating to 845°C (1550°F) for 24 hours followed by air cooling. - Age harden at 760°C (1400°F) for 16 hours followed by air cooling (resultant hardness 34-40 HRC.) B. For optimum room- and high-temperature tensile properties: Solution heat treat at 995-1035°C (1825-1895°F) for 4 hours followed by oil quench.	Monel K500	products and 1040°C (1900°F) for cold-drawn products for optimum response to subsequent age hardening. <sup>2</sup> The following age-hardening procedures are recommended for achievement of maximum properties <sup>aa</sup> : A. Soft material (140-180 Brinell, 75-90 RB). Hold for 16 hours at 590°C – 610°C (1100°F - 1125°) F followed by furnace cooling at the rate of 15 to 25°F per hour to 480°C (900°F). Cooling from 900°F to room temperature may be carried out by furnace or air cooling, or by quenching, without regard for cooling rate. <sup>bb</sup> B. Moderately cold-worked material (175-250 Brinell, 8-25 RB). Hold for 8 hours or longer at 1100 to 1125°F, followed by cooling to 900°F at a rate not to exceed 8°C – 14°C (15°F - 25°F) per hour. Higher hardness can be obtained by holding for as long as 16 hours at temperature, particularly if the material has been cold-worked only slightly. As a general rule, material with an initial hardness of 175-200 Brinell should be held the full 16 hrs. Material close to the top end (250 Brinell or 25 HRc) should attain full hardness in 8 hours. <sup>cc</sup> C. Fully cold-worked material (260-325 Brinell, 25-35 Rc). Hold for 6 hours or longer at 525C – 540C (980F - 1000°F)
<ul> <li>A. For optimum high-temperature creep and stress-rupture properties:         <ul> <li>Solution treat at 1080°C (1975°F) for 4 hours followed by air cooling (anticipated hardness: 20-25 HRC).</li> <li>Stabilization by heating to 845°C (1550°F) for 24 hours followed by air cooling.</li> <li>Age harden at 760°C (1400°F) for 16 hours followed by air cooling (resultant hardness 34-40 HRC.)</li> <li>B. For optimum room- and high-temperature tensile properties:</li> <li>Solution heat treat at 995-1035°C (1825-1895°F) for 4 hours followed by oil quench.</li> </ul> </li> </ul>	904L SS	Harden by solution heat-treat at 1090°C - 1175°C (1995°F - 2150°F) followed by rapid cooling.
Age harden at 760°C (1400°F) for 16 hours followed by air cooling (resultant hardness: 34-44 HRC.	Waspaloy	<ul> <li>A. For optimum high-temperature creep and stress-rupture properties:</li> <li>Solution treat at 1080°C (1975°F) for 4 hours followed by air cooling (anticipated hardness: 20-25 HRC).</li> <li>Stabilization by heating to 845°C (1550°F) for 24 hours followed by air cooling.</li> <li>Age harden at 760°C (1400°F) for 16 hours followed by air cooling (resultant hardness 34-40 HRC.)</li> <li>B. For optimum room- and high-temperature tensile properties:</li> <li>Solution heat treat at 995-1035°C (1825-1895°F) for 4 hours followed by air cooling.</li> <li>Stabilization by heat to 845°C (1550°F) for 4 hours followed by air cooling.</li> </ul>
AL6XN Annealed between 1110°C (2025°F) and 1230°C (2250°F) followed by rapid (gas) cooling <sup>ee</sup> .	AL6XN	Annealed between 1110°C (2025°F) and 1230°C (2250°F) followed by rapid (gas) cooling <sup>ee</sup> .



Notes

- [a] ASTM A638 Grade 660 Type 2; ASTM A453 Grade 660 Class B; ASTM A891 Type 2; AMS 5732.
- [b] ASTM A638 Grade 660 Type 1; ASTM A453 Grade 660 Class A, ASTM A891 Type 1; AMS 5737.
- [c] Fixture the workpiece to minimize distortion as this alloy has low strength at the annealing temperature.
- [d] If the cooling is too slow, the corrosion resistance of RA2205 stainless will be markedly decreased. Furnace cooling of RA2205 stainless is definitely not recommended, and would result in quite unacceptable mechanical and corrosion properties.
- [e] Haynes International alloy.
- [f] Depending on the product form.
- [g] Annealing at temperatures lower than the solution heat-treating temperatures will produce carbide precipitation, which may marginally affect the alloy's strength and ductility.
- [h] Required temperature uniformity is ± 10°C (± 18°F) or better. Adequate time must be allowed so as to ensure that the section is fully soaked throughout at temperature. Quenching must be carried out immediately on removal from the furnace, with the minimum of cooling in air during transfer to the quench tank.
- [i] Depending upon the nature of the component, the extent of machining and the tolerances required, this treatment may be carried out at one or more stages of the machining cycle.
- [j] This treatment applies to both solution annealing and stress relieving. Stress relief treatments at any lower temperature carry the risk of precipitation of detrimental intermetallic or nonmetallic phases.
- [k] Annealing at higher temperatures is acceptable, but this will increase the amount of ferrite present in the microstructure.
- [I] Solution heat treat and quench after either hot or cold forming.
- [m] To obtain maximum corrosion resistance, heat treated products should be pickled and rinsed.
- [n] Grain growth does not occur until the alloy is heated to about 980°C (1800°F). At that temperature, the finely dispersed carbide particles in the alloy's microstructure, which inhibit grain growth, begin to coalesce.
- [o] Solution of the carbides begins at about 1040°C (1900°F). Treatment for 1 - 2 hours dissolves the carbides completely and results in increased grain size.
- [p] If the material is to be machined, formed, or welded, it typically is purchased in the mill annealed or stress relieved condition. The material is then fabricated in its most malleable condition. After fabrication, it can be heat treated as required per the applicable specification.
- [q] Cold forming may be done using standard tooling although plain carbon tool steels are not recommended as they tend to produce galling. Soft die materials (bronze, zinc alloys, etc.) minimize galling and produce good finishes, but die life is somewhat short. For long production runs, the alloy tool steels, (D-2, D-3) and highspeed steels (T-1, M-2, M-10) give good results, especially if hard chromium plated to reduce galling. Tooling should be such as to allow for liberal clearances and radii. Heavy duty lubricants should be used to minimize galling in all forming operations. Bending of sheet or plate through 180° is generally limited to a bend radius of 1 T for material up to .1 250" thick (3.175 mm) and 2 T for material thicker than .1 250" (3.175 mm).

- [r] Hot working may be done but should be performed at temperatures under 925°C (1700°F) to maintain optimum corrosion resistance of the alloy.
- [s] For optimal corrosion resistance, cool from solution heattreatment temperatures to black (540°C / 1000°F) in two minutes or less. Stress relief heat treatments are not effective with this alloy and a full anneal should be conducted where stress relief heat treatment of other materials would be considered.
- [t] For bright annealed sheet or coil products solution treat at 1150°C (2100°F) and cool in hydrogen.
- [u] Parts which have been hot formed should be solution annealed prior to final fabrication or installation.
- [v] Hardened by cold work only.
- [w] Grain growth is rapid in this alloy, so use the lower end of the temperature range and minimal time to retain good strength.
- [x] Marked increase in the proof stress, without affecting other properties.
- [y] Performed both for softening of the matrix after working and for solutioning of the age-hardening phase.
- [z] Grain growth becomes fairly rapid above 980°C (1800°F), and if a fine-grained structure is desired heating time should be kept to a minimum at higher temperatures. For optimum aging response and maximum softness, it is important to obtain an effective water quench from the heating temperature without delay. A delay in quenching or a slow quench can result in partial precipitation of the age-hardening phase and subsequent impairment of the aging response. Addition of about 2% alcohol (by volume) to the water will minimize oxidation and facilitate pickling.
- [aa] Procedures described will usually result in higher properties. In some instances it may be desired to decrease the time, either for cost saving or for obtaining intermediate properties. Test runs should be performed to determine actual properties obtained.
- [bb] This procedure is suitable for as-forged and quenched or annealing forgings, for annealed or hot-rolled rods and large cold-drawn rods (over 40 mm (1-1/2") diameter) and for soft -temper wire and strip.
- [cc] These procedures are applicable to cold-drawn rods, haft-hard strip, cold-upset pieces and intermediate-temper wire.
- [dd] In some instances slightly higher hardness may be obtained (particularly with material near the lower end of the hardness range) by holding 8 to 10 hours at temperature. This procedure is suitable for spring-temper strip, spring wire or heavily coldworked pieces such as small, cold-formed balls. Cooling may be done in steps of 38°C(100°F), holding the furnace 4 to 6 hours at each step.
- [ee] Cooling at relatively slow rates increases the potential for precipitating sigma or chi phases, which generally detract from the corrosion resistance of the material. Nitrogen addition to this alloy slows but does not eliminate the tendency to precipitate these phases in the approximate temperature range 1040°C to 540°C (1900°F to 1000°F). Annealing in air (or other oxidizing atmospheres) causes the formation of chromium-rich oxide scales. Conditions such as long anneals, leaky furnaces, poor atmosphere circulation and heavy pre-existing scale should be avoided as these conditions may lead to the condition called catastrophic oxidation, which can create pits on the metal surface.

### **In Conclusion**

The heat treatment of specialty fasteners is an important segment of the overall heat treatment industry and demands careful control of both process and equipment in order to achieve the high performance requirements demanded by the industries for which they are intended.

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