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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[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**).

Table 1. Classification of Exotic Alloys for Specialty Fasteners

Class	Alloy	Examples
0	Steels [a]	A286
1A	Stainless Steels [b]	Alloy 20, Alloy 50, Alloy 60, Custom 450, Carpenter 21, Carpenter CB3, 904L, AL6XN, Avesta 254SMo
1B	Stainless Steels [a]	13-8, 17-4, 17-7
1C	Stainless Steels [c]	2304, 2205, 2507, 2707, 3207, Ferralium 255-SD50
1D	Stainless Steels [d]	50, 60
2A	Superalloys [e]	B, C-276, C-2000, C-22, C-4, G, X
2B	Superalloys [f]	230, HR120, HR160, ULTIMET 1233
2C	Superalloys [g]	600, 601, 615, 718, 800/800H, 825, 925, X750, 25-6Mo
2D	Superalloys [h]	Waspaloy
3A	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.

Table 2A. Select Class 1 – Nominal Alloy Chemistries

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
Mo	2 - 3	1.5 - 3	0.50 – 1.0	6 - 7	-	-	4 – 5
Mn	2.0 [b]	4 - 6	1.0 [b]	2.0 [b]	1.0 [b]	1 [b]	2.0 [b]
Si	1.0 [b]	1.0 [b]	1.0 [b]	1.0 [b]	1.0 [b]	1.0 [b]	1.0 [b]
N	-	0.20 – 0.40		0.18 – 0.25	-	-	-
Al	-	-		-	-	0.75 – 1.5	-
C	0.060 [b]	0.060 [b]	0.050 [b]	0.030 [b]	0.07 [b]	0.09 [b]	0.02 [b]
S	0.035 [b]	0.010 [b]	0.030 [b]	0.03 [b]	0.030 [b]	0.040 [b]	0.035 [b]
Cu	3 - 4	-	1.25 – 1.75	0.75 [b]	3 - 5	-	1 – 2
Nb	-	0.10 – 0.30	-	-	-	-	-
P	0.035 [b]	0.040 [b]	0.030 [b]	0.04 [b]	0.040 [b]	0.040 [b]	0.045 [b]
V	-	0.10 – 0.30	-	-	-	-	-
Cb + Ta	[d]	-	-	-	0.15 – 0.45	-	-

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 [b]	2 [b]	6 - 10	[c]	22 [a]	4.0 – 7.0
Ni	37	37 [c]	72 [a]	50 – 55	42 – 46	55.0
Co	3 [c]	29		1.00 [b]	-	2.5 [b]
Cr	25	28	14 – 17	17 – 21	19.5 – 22.5	14.5 – 16.5
Mo	2.5 [c]	1 [c]	-	2.8 – 3.3	2.5 – 3.5	15 – 17
W	2.5 [c]	1 [c]	-	-	-	3.0 – 4.5
Cb	0.7	1 [c]	-	-	-	-
Mn	0.7	0.50	1.0 [b]	0.35 [b]	1.0 [b]	1.0 [b]
Si	0.6	2.75	0.5 [b]	0.35 [b]	0.5 [b]	0.08 [b]
N	0.20	-	-		-	-
Al	0.1	-	-	0.20 – 0.80	0.1 – 0.5	-
C	0.05	0.05	0.15 [b]	0.08 [b]	0.03 [b]	0.010 [b]
B	0.004	-	-	0.006 [b]	-	-
Ti	-	0.5	-	0.65 – 1.15	1.9 – 2.4	-
S	-	-	0.015 [b]	0.015 [b]	0.030 [b]	0.030 [b]
Cu	-	-	0.50 [b]	0.30 [b]	1.5 – 3.0	-
Nb	-	-	-	4.75 – 5.50	0.5 [b]	-
P	-	-	-	0.015 [b]	-	0.04 [b]
V	-	-	-	-	-	0.35 [b]

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

Table 2C.
Select Class 3 – Nominal Alloy Chemistries

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

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 and continuous (**Fig. Nos. 2 – 3**) 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)

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

Table 4.
Heat Treatments for Exotic Fastener Alloys

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. [a] 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. [b]
Avesta 2205	Solution anneal at 1020°C - 1100°C (1870°F - 2010°F) followed by water quench. [c, d]
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. [f]
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. [g]

Alloy	Heat Treatment
Ferralium 255-SD50	Solution heat treat at 1070°C (1960°F) followed by a rapid quench, preferably in water.[h] A stress relief heat treatment, when required, should be carried out by heating to 350°C (660°F), holding for two (2) hours at temperature followed by air cool.[i]
Duplex Alloy 2205	Anneal at 1040°C (1900°F), followed by rapid cooling, ideally by water quenching.[j]
Duplex Alloy 2304	Anneal at 980°C (1800°F) followed by rapid cooling to prevent the precipitation of undesirable phases.[k]
Super Duplex Alloy 2507	Solution anneal at a minimum of 1050C (1925°F) following by rapid air or water quench.[l, m]
Hyper Duplex Alloy 3207	Solution anneal at 1040°C - 1140°C (1905°F - 2085°F) followed by rapid cooling in air, protective atmosphere or water.
Inconel 600	Anneal at 1010°C (1850°F) for 15 minutes. Brief exposure to 1040°C (1900°F) will give soft material without producing a coarse grain structure. Anneal at 1090°C - 1150°C (2000° - 2100°F) for 1 – 2 hours to obtain maximum creep and rupture strength.[o]
Inconel 718	Two heat treatments are commonly used: •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. •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, followed by air cooling.[p]
Inconel 825	Hardened by cold work only. Anneal at 955°C (1750°F) with rapid air cool.[q, r]
Inconel 925	Solution anneal at 980°C (1800°F - 1900°F) and air cool. Aging at 730°C (1350°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	Normally furnished in the solution heat-treated condition. Solution treat at 1040°C -1150°C (1900°F - 2100°F) and rapidly cooled.[s]
Hastelloy B3	Normally furnished in the solution heat-treated condition. Solution treat at 1065°C (1950°F) and rapid quench.[t]
Hastelloy G30	Solution heat treatment consists at 1180°C (2150°F) followed by rapid air-cooling or water quenching.[u]
Hastelloy C-2000	Solution anneal at 1135°C (2075°F) followed by rapid air-cooling or water quenching.[v]
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.[w] Stress relief, if required, is at 540-570°C. Stress relief of cold worked material at 300°C (510°F).[x]
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.
Monel K500	Anneal in the range of 750°C – 870°C (1400°F -1600°F).[y] 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.[z] The following age-hardening procedures are recommended for achievement of maximum properties[aa]: 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.[bb] 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.[cc] C. Fully cold-worked material (260-325 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.[dd]
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 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. Stabilization by heat to 845°C (1550°F) for 4 hours followed by air cooling. Age harden at 760°C (1400°F) for 16 hours followed by air cooling (resultant hardness: 34-44 HRC.
AL6XN	Annealed between 1110°C (2025°F) and 1230°C (2250°F) followed by rapid (gas) cooling[ee].

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.
[l] 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 high-speed 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 heat-treatment 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 cold-worked 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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