Fabricating the Special Metals Corporation Alloys

Nickel alloys are readily fabricated by standard deformation-forming processes. The fabrication methods discussed in this bulletin are usually classified as secondary forming processes. Primary forming methods such as rolling-mill and draw-bench operations are not within the scope of this bulletin.

This publication describes general fabrication methods for guidance only. Specific procedures depend on such factors as available equipment and intended use of the component. Values for material properties are typical but are not suitable for specifications.

Procedures for heating and pickling outlined in this bulletin are the general practices commonly used for the alloys. Heating and pickling for highly specialized purposes may require deviation from these guidelines. In such cases, specific recommendations should be obtained from **Special Metals Corporation.**

Nominal chemical compositions and mechanical-property ranges for representative **Special Metals Alloys are** given in the Appendix. Complete descriptions of individual alloys are given in separate bulletins. These publications should be consulted before materials are selected for specific applications. Additional information on available mill products may be obtained by contacting the sources listed on the back cover of this bulletin.

Cold Forming

Introduction

The excellent ductility and malleability of the SMC alloys in the annealed condition make them adaptable to virtually all methods of cold fabrication. As other engineering properties vary within this group of alloys, formability ranges from moderately easy to difficult in relation to other materials.

Resistance to Deformation

Resistance to deformation, usually expressed in terms of hardness or yield strength, is a primary consideration in cold forming. Deformation resistance is moderately low for the nickel and nickel-copper systems and moderately high for the nickel-chromium and nickel-iron-chromium systems. However, when properly annealed, even the high-strength alloys have a substantial range between yield and ultimate tensile strength. This range is the plastic region of the material and all cold forming is accomplished within the limits of this region. Hence, the high-strength alloys require only stronger tooling and more powerful equipment for successful cold forming. Nominal tensile properties and hardnesses for some Inco alloys in various forms are shown in the Appendix.

Strain Hardening

A universal characteristic of the high-nickel alloys is that they have face-centered cubic crystallographic structures, and, consequently, are subject to rapid strain hardening. This characteristic is used to advantage in increasing the room-temperature tensile properties and hardness of alloys which otherwise would have low mechanical strength, or in adding strength to those alloys which are hardened by a precipitation heat treatment. Because of this increased strength, large reductions or extensive draws can be made without rupture of the material. However, the number of reductions in a forming sequence will be limited before annealing is required, and the percentage reduction in each successive operation must be reduced rapidly.

Since strain hardening is related to the solid-solution strengthening of alloying elements, the strain-hardening rate generally increases with the complexity of the alloy. Accordingly, strain-hardening rates range from moderately low for Nickel, the NILO, and the MONEL alloys to moderately high for the INCONEL, NIMONIC, and INCOLOY alloys. Similarly, the age-hardenable alloys have higher strain-hardening rates than their solid-solution equivalents. Figure 1 compares the strain-hardening rates of some SMC alloys with those of other materials as shown by the increase in hardness with increasing cold reduction. Note that the strain-hardening rate of most of the alloys is greater than that of mild steel and less than that of Type 304 stainless steel.

Because the modulus of elasticity of the high-nickel alloys is relatively high (similar to that of the ferrous alloys), a small amount of springback in cold-forming operations might be expected. However, springback is also a function of proportional limit, which can increase greatly during cold working of strain-hardenable materials. For instance, a yield strength of 25 000 psi (172 MPa) of an alloy in the annealed condition might increase to 75 000 psi (517 MPa) during a drawing operation. Therefore, springback must be computed from the higher yield strength, rather than from the initial value. Modulus of elasticity values for some Inco alloys are given in Table 1.

Table 1—Modulus of Elasticity of **Special Metals Alloys**

Material	Tension		Torsion	
	psi x 10^6	GPa	psi x 10^6	GPa
Nickel 200	30	207	11	76
DURANICKEL alloy 301	30	207	11	76
MONEL alloy 400	26	179	10	69
MONEL alloy K-500	26	179	10	69
INCONEL alloy 600	31	214	11	76
INCONEL alloy 625	30	207	11	76
INCOLOY alloy 800	28	193	11	76
NIMONIC alloy 75	32	221	-	-
NIMONIC alloy 80A	32	221	12	85

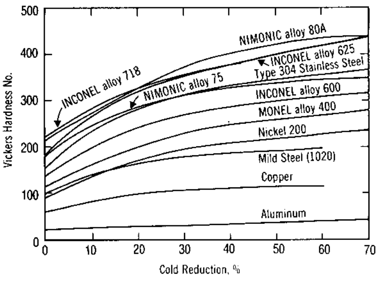

Figure 1. Effect of cold work on hardness.

Lüders Lines

When in the fully annealed condition, Nickel 200, Nickel 201, and Nickel 270 have a tendency to form Lüders lines (also known as stretcher strains, breaker lines, and fluting) during cold forming. Lüders lines result from selective yielding, which is exhibited on a stress-strain diagram as a knee or as upper and lower yield points.

Lüders lines have no significant effect on mechanical properties or fabricability but should be avoided if smooth bends, precision flatness, or good appearance is required. Lüders lines can be prevented in sheet and strip by running the material through a staggered-roll leveler or by giving it a light tempering pass (1 to 2% reduction) prior to forming.

Galling

Because the high-nickel alloys do not readily develop an oxide film which would present a barrier to diffusion bonding, the alloys tend to cold weld (gall) easily to materials of similar atomic diameter. Also, the alloys are relatively soft and ductile in the annealed temper and tend to flow into intimate contact with mating surfaces. When a cold weld is formed, the high shear strength and ductility of the alloys prevent the weld from being broken easily. For these reasons, the coefficient of friction between the high-nickel alloys and other metals, including most die materials, is usually high.

Alloying with highly reactive elements which tend to form oxide films readily, such as chromium, reduces the galling or cold-welding propensity of the metal. Accordingly, the nickel-chromium and nickel-iron-chromium alloys are less prone to gall than are the nickel and nickel-copper alloys. However, these chromium oxide films are thin and brittle and provide only limited protection since they are easily broken when the substrate is deformed. The use of heavy-duty lubricants will minimize galling in most cold-forming operations.

Lubricants

Lubricants are used to prevent galling during cold forming and also to prevent rapid wear of the forming dies. Most cold forming of the Inco alloys requires heavy-duty lubricants.

Unsaturated or polar fatty-acid oils and vegetable oils have good surface attraction. Even when diluted, they are good lubricants for moderate deep-drawing operations on sheet and strip.

Extreme-pressure lubricants usually contain sulfur or chlorine. These elements increase the effectiveness of lubricants by forming intermetallic compounds on freshly abraded metal surfaces that have been stripped of their diffusion-barring oxide coatings. The compounds formed have low shear strengths and, since they are porous, hold lubricating oil at high forming pressures. The metal interface must reach a temperature of several hundred degrees before the sulfur and chlorine will be liberated from their organic bonds within the lubricant and react with the metal. Therefore, these elements are not beneficial in light forming operations which do not generate sufficient heat to cause reaction. In the deep drawing of thick sheet and plate or in high-speed forming operations in which considerable heat is generated, sulfurized and chlorinated lubricants are useful.

Although sulfur and chlorine can improve lubricants, they can also have harmful effects if not completely removed after forming. Sulfur will embrittle the high-nickel alloys at the elevated temperatures encountered in such operations as annealing or age hardening, and chlorine can cause pitting of the alloys after long exposure. Therefore, sulfurized and chlorinated lubricants should not be used if any difficulty is anticipated in cleaning the formed part. These lubricants are not recommended for use in spinning, as this operation tends to burnish the lubricant into the surface of the metal. Similarly, molybdenum disulfide is seldom recommended for use with the high-nickel alloys because of the difficulty in removing it.

Solid or semi-solid lubricants such as soap, tallow, wax, or pigmented oils often require special hand application or tank dipping and are usually used only when necessary, such as in the deep drawing of thick sheet and strip. Solid lubricants such as bar soap and beeswax are often used in spinning operations since they can be applied easily by holding a bar of the lubricant against the rotating blank.

Metallic stearate soaps have low polar attraction for metals and require a carrier if applied as a dry powder. Lime, borax, sodium silicate, oxide, oxalate, and copper can be used as carriers for metallic stearate soaps. The proper carrier for any specific use will depend upon the particular alloy and forming process used.

Pigmented oils and greases should be selected with care as the pigment might be white lead (lead carbonate), zinc oxide, or similar metallic compounds that have low melting points. These elements can embrittle the high-nickel alloys if the compounds are left on the metal during heat treatment. Inert fillers such as talc or flour can be safely used.

Because application and removal are relatively expensive, metallic coatings such as copper are used as lubricants only in severe cold-forming operations and then only when they can be properly removed.

Ordinary petroleum greases are not normally used in forming the high-nickel alloys. These greases do not necessarily have the lubricating characteristics indicated by their viscosity and they do not have a strong polar attraction for metals.

Phosphates do not form usable intermetallic surface compounds on the high-nickel alloys and cannot be used as lubricant carriers.

Light-bodied mineral oils and water-base lubricants have limited lubricity and can be used only in light forming operations.

Tools and Equipment

The SMC alloys do not require special equipment for cold forming. However, the physical and mechanical properties of the high-nickel alloys frequently necessitate modification of tools and dies used for cold forming other materials. These modifications are discussed in this section. Information applying to specific cold-forming operations may be found in subsequent sections covering those operations.

Die Materials

Plain carbon tool steels (water-hardening W-1, W-2) are not recommended for use as die materials on the high-nickel alloys because of the galling tendencies between these two types of materials. Oil-hardening steels (O-1, O-6) offer some improvement but are not completely satisfactory. Most other commercial tool and die materials are satisfactory for use with the alloys.

Soft die materials such as aluminum-bronze, nickel-aluminum-bronze, and certain zinc alloys are used when superior surface finishes are desired. However, these materials have a relatively short service life. Parts formed with zinc-alloy dies should be flash-pickled in dilute nitric acid to remove any traces of zinc picked up from the dies during forming. Zinc can cause embrittlement of the high-nickel alloys during heat treatment or high-temperature service. For similar reasons, parts formed with brass or bronze dies should be pickled if the dies impart a bronze color to the workpiece.

Large dies, such as those used in the forming of sheet, are made of gray cast iron, white cast iron, or ductile iron because of the low cost of these materials. These metals are compatible with the high-nickel alloys but have a service life suitable only for short to medium production runs.

Long production runs justify the use of alloy tool steels such as high-carbon high-chromium steels (D-2, D-3, D-4), air-hardening steel (A-2), and high-speed steels (T-1, M-2, M-10). For extended service and improved surface finish, these alloy tool steels may be hard chromium plated. Water- and oil-hardening steels can also be chromium plated to reduce galling, but it is difficult to maintain the plating for extended periods of use.

Carbide dies provide maximum length of service and are often economically justified for long production runs of small parts. The high tensile and impact loads encountered in the forming of large parts inhibit the use of carbide for large dies.

Nonmetallic die materials such as hardwoods, (birch, maple) and plastics (nylon, Teflon*), because of their low galling tendencies with the high-nickel alloys, work well in light forming operations such as the spinning of thin sheet. Similarly, synthetic rubbers such as neoprene and urethane work well as male-die components in rubber-pad forming and hydroforming.

Tool Design

Because of the galling tendency of the high-nickel alloys and because of the high pressures developed in forming, tooling should be designed with liberal radii, fillets, and clearances. The high-nickel alloys have good flow characteristics, and large radii and clearances can be used without causing wrinkling and buckling. If wrinkling does occur, and it becomes necessary to decrease punch and draw-ring radii, a lubricant of greater film strength may be required to offset the increase in wear and galling. Similarly, if clearances are decreased for the purpose of ironing or burnishing, an improvement may be required in the lubricant or die material.

The radii and clearances used in the cold forming of high-nickel alloys are usually larger than those used for brass and mild steel, and approximately equal to those used for the austenitic stainless steels.

Because the high-nickel alloys, particularly the INCONEL and NIMONIC nickel-chromium alloys, have higher yield strengths and strain-hardening rates, they require stronger and harder dies and more powerful equipment than does mild steel. Generally, 30 to 50% more power is required for the high-nickel alloys than mild steel.

Equipment Operation

The strain-rate sensitivity and frictional characteristics of the SMC alloys dictate that all forming operations, exclusive of high-energy-rate operations, be performed at relatively slow speeds. For instance, crank or ram speed in shearing, deep drawing, and brake bending is usually 30 to 50 ft/min (10 to 15 m/min). Cold heading, perforating, and similar operations are normally performed at speeds of 60 to 100 strokes per minute.

Material

Complete descriptions of individual alloys are given in the bulletins pertaining to those alloys. These publications should be consulted before selecting material for specific applications.

Temper

Most cold-forming operations require the use of annealed material. However, the softer alloys such as Nickel 200, the NILO alloys, and MONEL alloy 400 are often used in skin-hard and ¼-hard tempers to improve shearing and perforating characteristics. For similar reasons, MONEL alloy 400 for fastener applications is usually cold-headed in No. 1 or 0 temper. Also, tempered material is used in mild forming operations when greater strength or spring properties are desired in the finished product.

*Trademark of E. I. DuPont de Nemours & Co.

Finish

The surface finish on material to be cold formed should be compatible with the method of forming. Generally, the most important characteristic of the material surface is that of having the ability to hold sufficient lubricant to prevent excessive galling and die wear. Cold-rolled annealed and pickled, and cold-rolled bright-annealed sheet and strip have finishes suitable for deep drawing and spinning.

Hot-rolled plate with an annealed and descaled finish is suitable for most forming. If improved surface finishes are desired, they can be obtained by grinding or polishing the material after forming.

Rod and wire rod to be used for cold heading, cold extrusion, thread rolling, or swaging should have high surface quality to reduce the possibility of surface rupturing during forming. Suitable surface quality can be obtained in cold-drawn rod by centerless grinding, in hot-finished material by rough turning or centerless grinding, and in wire rod by shaving or centerless grinding. Hot-finished bolt-tolerance rod and wire rod have improved shape and dimensional tolerances but their surface quality is the same as that of the standard hot-finished product. Bolt-tolerance material is produced by giving the material a cold-drawing pass for sizing only.

Standard forms of tube and pipe are suitable for most cold-forming processes. However, tubular products should be qualified with a standard flare test to ensure their capacity for internal forming such as bulging, flaring, and expanding.

As-extruded tubing usually has adequate softness and ductility in the extruded temper for most forming operations. As-extruded tubing, however, has a rough surface which must be taken into consideration in forming.

Forming of sheet, strip, and plate

Sheet and related products can be cold-formed by many methods. This section discusses the most common processes as they apply to Inco alloys. The methods discussed are shearing, blanking, perforating, deep drawing, and spinning. Other methods, such as dimpling, beading, coining, and stretch forming, are either variations of the above processes or are performed in a similar manner and are not described in this bulletin.

Bending

A guide to the minimum bend diameters of hot-rolled and annealed plate and annealed sheet and strip is given in Table 2. In the determination of those diameters a sample is judged to have passed the 180°-bend test if its surface shows no ductile fracturing. Because of the effect of various surface conditions and heat treatments on bendability, the bends cannot be guaranteed. Many of the materials can nevertheless be bent in stages to tighter bends than those that are suggested in Table 2, provided that the initial bend is not severe. Consult Special Metals Corp. for further information.

The importance of surface condition is demonstrated by the alloys from which scale or oxides must be removed to assure successful bending. As indicated in Table 2, achieving the minimum bend diameters depends upon the removal of scale by pickling MONEL alloy 400 plate and the grinding or machining of the various forms of INCONEL alloy 625 and INCONEL alloy 718.

Shearing, Blanking, and Perforating

These operations are best performed on tempered sheet and strip unless subsequent forming

Table 2—Minimum Bend Diameters for Annealed Sheet and Strip and Hot-Rolled and Annealed Plate in 180° Bend

	Thickness (T)		Minimum Diameter[a]
Alloy	in.	mm	
Nickel 200	Sheet and Strip 0.012-0.250	Sheet and Strip 0.30-6.35	1T
	Plate 0.187-0.250	Plate 4.75-6.35	2T
MONEL alloy 400	Sheet and Strip 0.012-0.049 0.050-0.109[b] 0.110-0.250[b]	Sheet and Strip 0.30-1.24 1.27-2.77[b] 2.79-6.35[b]	1T 1T 2T
	Plate[c] 0.187-0.250	Plate[c] 4.75-6.35	2T
INCONEL alloy 600	Sheet and Strip 0.012-0.250	Sheet and Strip 0.30-6.35	1T
	Plate 0.187-0.250	Plate 4.75-6.35	2T
INCONEL alloy 625[d]	Sheet and Strip 0.012-0.250	Sheet and Strip 0.30-6.35	2T
	Plate 0.187-0.250	Plate 4.75-6.35	2T
INCONEL alloy 718[d]	Sheet and Strip 0.012-0.049 0.050-0.250	Sheet and Strip 0.30-1.24 1.27-6.35	1T 2T
INCONEL alloy X-750	Sheet and Strip 0.012-0.049 0.050-0.250	Sheet and Strip 0.30-1.24 1.27-6.35	1T 2T
INCOLOY alloy 800	Sheet and Strip 0.012-0.049 0.050-0.109[b] 0.110-0.250	Sheet and Strip 0.30-1.24 1.27-2.77[b] 2.79-6.35	1T 1T 1T
	Plate[b] 0.187-0.250	Plate[b] 4.75-6.35	2T
INCOLOY alloy 825	Sheet and Strip 0.012-0.049 0.050-0.250[b]	Sheet and Strip 0.30-1.24 1.27-6.35[b]	2T 2T
	Plate[b] 0.187-0.250	Plate[b] 4.75-6.35	2T

[a] Bend tests were performed according to ASTM Standard Method E 290-77 with a guided-bend jig as described in ASTM Standard Method E 190-64 (Reapproved 1976).

[b] Successful bend depended upon surface condition of the samples, with particular regard to freedom from oxidation.

[c] Samples of MONEL alloy 400 plate were descaled.

[d] Sheared edges of samples of INCONEL alloys 625 and 718 were ground or machined.

operations dictate that the starting material be in the annealed condition. The optimum temper for shearing, blanking, and perforating will vary, depending on the alloy and the thickness of the material being formed. For instance, thin strip of Nickel 200 and the NILO alloys should be blanked in full-hard temper for maximum die life and minimum edge burr. Annealed temper is usually suitable for blanking a precipitation-hardenable alloy like INCONEL alloy X-750 and NIMONIC alloy 80A.

Equipment

High-carbon high-chromium steels (D-2, D-4), high-speed tool steels (T-1, M-2), and carbide are the best materials for punches and blanking tools.

Punch and die clearances should be 3 to 5% of the stock thickness for thin material and 5 to 10% of the stock thickness for thick material—⅛ in. (3 mm) and over. The clearance between the punch and stripper plate should be as little as practicable. For maximum rigidity, punches should be as short as possible; sleeve-supported punches can be used for additional strength. Also, positive-hold stripper plates should be used to prevent the workpiece from shifting. Punches must be dressed often and kept sharp to minimize shear loading of the tool and to reduce work hardening and burring of the workpiece. Short strokes and slow operating speeds also reduce impact loads.

Where possible, as on large diameters, punches should be hollow ground to provide some back rake to the cutting edge. Curving or slanting the cutting edge and staggering the length of gang punches also lessen impact loads.

Shearing equipment should have a mild-steel rating 50% greater than the size of the nickel-alloy material to be sheared. For example, cutting ¼-in. (6.4 mm) thick MONEL alloy 400 plate would require a shear with a mild-steel rating of ⅜ in. (9.5 mm).

Lubricants

Lubricants are usually omitted in shearing but should be used in blanking and perforating. A light mineral oil fortified with lard oil can be used for material under ⅛ in. (3 mm) thick. A heavier sulfurized oil should be used for thicker material.

Procedure

In perforating, the minimum hole diameter is usually equal to or greater than the thickness of the material, depending on the thickness, temper, and specific alloy. Table 3 is a guide for establishing minimum hole diameters for given thicknesses of MONEL alloy 400, Nickel 200, and INCONEL alloy 600. Hole diameters equal to the thickness of the sheet have been produced in material as thin as 0.018 in. (0.46 mm), but only after considerable experience and with proper equipment.

The softer alloys, such as Nickel 200, have greater impact strengths than have the harder, chromium-containing alloys. Consequently, the softer alloys are more sensitive to the condition of dies and equipment. Shear knives may penetrate 65 to 75% of the material thickness before separation occurs in shearing Nickel 200, and only 20 to 30% in shearing the harder alloys.

Laboratory tests have indicated that the shear strength of the high-nickel alloys in double shear averages about 65% of the ultimate tensile strength (see Table 4). These values, however, were obtained under essentially static conditions using laboratory testing equipment having sharp edges and controlled clearances. Shear loads for well-maintained production equipment can be found in Table 5. These data were developed on a power shear having a ⅜ in./ft (31 mm/m) rake.

Table 3—Minimum Hole Diameters for Perforating Quarter-Hard Sheet of Nickel 200, MONEL alloy 400, and INCONEL alloy 600

Sheet Thickness		Minimum Hole Diameter
in.	mm	
0.018 to 0.034	0.46 - 0.86	1.5 x Thickness
0.037 to 0.070	0.94 - 1.8	1.3 x Thickness
0.078 to 0.140	2.0 - 3.6	1.2 x Thickness
5/32 and thicker	4.0 and thicker	1.0 x Thickness

Table 4—Strength in Double Shear

Alloy	Condition	Shear Strength		Tensile Strength		Hardness, Rockwell
		psi	MPa	psi	MPa	
Nickel 200	Annealed	52 000	359	68 000	469	46B
	Half-Hard	58 000	400	79 000	545	84B
	Full-Hard	75 000	517	121 000	834	100B
MONEL alloy 400	Hot-Rolled, Annealed	48 750	336	73 000	503	65B
	Cold-Rolled, Annealed	49 500	341	76 800	530	60B
INCONEL alloy 600	Annealed	60 800	419	85 000	586	71B
	Half-Hard	66 250	457	98 800	681	98B
	Full-Hard	82 400	568	152 200	1049	31C
INCONEL alloy X-750	Age Hardened[a]	112 500	776	171 000	1179	36C

[a]Mill-annealed and aged 1300°F (705°C)/20 h.

Table 5—Shear Load for Power Shearing of 0.250-in. (6.35-mm)-Gauge Annealed Nickel Alloys at a ⅜ in./ft (31 mm/m) Rake as Compared with Mild Steel

Alloy	Tensile Strength		Hardness, Rb	Shear Load		Shear Load in Percent of Same Gauge of Mild Steel
	psi	MPa		lb	kN	
Nickel 200	60 000	414	66	61 000	271	200
MONEL alloy 400	77 000	531	75	66 000	294	210
INCONEL alloy 600	92 000	634	79	51 000	227	160
INCONEL alloy 625	124 000	855	95	55 000	245	180
INCONEL alloy 718	121 000	834	98	50 000	222	160
INCONEL alloy X-750	111 000	765	88	57 000	254	180
Mild Steel	50 000	345	60	31 000	138	100

Deep Drawing of Circular Shells

The nickel alloys can be drawn into any shape that is feasible with deep-drawing steel. The high-nickel materials have physical characteristics different from those of deep-drawing steel, but not sufficiently so as to require different manipulation of dies for the average deep-drawing operation.

Most simple shapes can be deep-drawn in the high-nickel alloys using dies and tools designed for use on steel or copper-base alloys. However, when intricate shapes with accurate finished dimensions are required, minor die alterations are necessary. These alterations usually involve increasing clearances and enlarging the radius of the die ring or punch. Figure 2 illustrates the critical areas in designing deep-drawing tools.

The SMC alloys have good deep-drawing qualities, but have their own characteristic working and mechanical properties which must be considered in order to obtain the full value of their ductility in deep drawing.

Double-Action Operation

On double-acting presses (Figure 3), a well-balanced series of reductions* for thin —$\frac{1}{16}$ in. (1.6 mm) and under—cylindrical shells with no ironing would be 35 to 40% on the first, or cupping, operation and 15 to 25% on redraws. If the walls are held to size, the first and second operations may be the same as suggested above, but on further redrawing, the amount of reduction should be diminished about 5% on each successive redraw.

Although a reduction of up to 50% can be made in one operation, it is not advisable because of the possibility of excessive shell breakage. Also, large reductions may open the surface of the metal and cause difficulty in finishing.

Single-Action Operation

As with all metals, the depth to which the high-nickel alloys can be drawn in single-action presses without hold-down mechanisms (Figure 4) is controlled by the ratio of blank thickness to blank or shell diameter. For single-action drawing without hold-down pressure, the blank thickness should be at least 2% of the blank or shell diameter for reductions as much as 35%. With properly designed dies and sufficiently thick material, the reduction on the first (cupping) operation with a single-action setup may be made equal to those recommended for double-action dies, that is, 35 to 40%. Redraws should not exceed 20% reduction.

If the shell wall is to be ironed, the increased pressure on the bottom of the shell usually necessitates a decrease in the amount of reduction to prevent shell breakage. With reductions of 5% or less, the shell wall may be thinned as much as 30% in one draw. With medium reductions of about 12%, the thickness of the shell wall can be decreased about 15%. If the wall is to be reduced a large amount, the shell should first be drawn to the approximate size with little or no wall thinning and the ironing done last. If a good surface finish is desired, the final operation should have a burnishing effect with only a slight change in wall thickness.

*The term "reduction," as used in this section, refers to reduction of shell or blank diameter, not to area reduction. For example, a shell drawn from 10 to 6 in. (254 to 152 mm) has received 40% reduction.

Clearances

Because the nickel alloys possess higher mechanical properties than does deep-drawing-quality steel, the alloys have greater resistance to the wall thinning caused by the pressure of the punch on the bottom of the shell. Consequently, greater die clearance is required than for steel if the natural flow of the metal is not to be resisted. However, the clearances required for the high-nickel alloys are only slightly greater than those

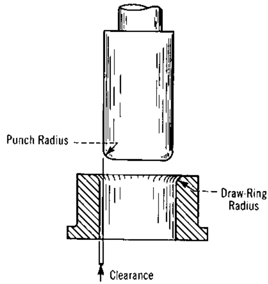

Figure 2. Critical areas in designing deep-drawing equipment.

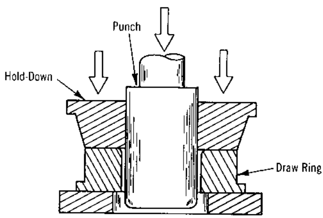

Figure 3. Double-action deep-drawing press.

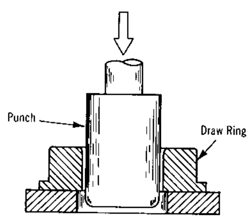

Figure 4. Single-action deep-drawing press without hold-down.

required for steel, and if dies used for steel have greater than minimum clearances they can often be used for the high-nickel materials.

For ordinary deep drawing of cylindrical shells an overall clearance of 40 to 50% of the blank thickness is sufficient and will prevent the formation of wrinkles. In the drawing of sheet thicker than 1/16 in. (1.6 mm), it is a general practice to have the inside diameter of the die ring larger than the diameter of the punch by three times the thickness of the blank.

Draw-Ring and Punch Radii

Because of the tendency of the high-nickel alloys to work harden rapidly, relatively large draw-ring and punch radii should be used, especially for the early operations of a series of draws. The high-nickel alloys require more power to draw than does steel, and, consequently, the punch imposes a greater stress on the bottom corner of the shell. Small punch radii cause thinning of the shell at the line of contact, and if such a shell is further reduced the thinned areas will appear farther up the shell wall and may result in visible necking or rupture. Also, buffing a shell having thinned areas will cause the shell wall to have a wavy appearance. For redraws, it is preferable to draw over a beveled edge and avoid round-edged punches except for the final draw.

The draw-ring radius for a circular die is governed principally by the thickness of the material to be drawn and the amount of reduction to be made. A general rule that can be used as a guide for light-gauge material is to have the draw-ring radius from five to twelve times the thickness of the metal. An insufficient draw-ring radius may result in galling and excessive thinning of the wall.

Deep Drawing of Rectangular Shells

As with other materials, the depth to which nickel-alloy rectangular shapes can be drawn in one operation is governed principally by the corner radius. To permit drawing to substantial depths, the corner radius should be as large as possible. Even with large corner radii, the depth of draw should be no more than two to five times the corner radius for MONEL alloy 400, the NILO alloys, Nickel 200, and Nickel 201, and four times the corner radius for INCONEL alloy 600 and NIMONIC alloy 75. The depth permissible also depends on the dimensions of the shape, and on whether the shape has straight or tapered sides. The depth of draw for material under 0.025 in. (0.64 mm) thick should not exceed an amount equal to three times the corner radius for MONEL alloy 400, the NILO alloys, Nickel 200, and Nickel 201, and less for INCONEL alloy 600 and NIMONIC alloy 75.

The corner radius on the drawing edge of the die should be approximately four to ten times the thickness of the material. It is essential that the blank not be released too soon if wrinkles around the top corner of the shape are to be avoided.

In redrawing for the purpose of sharpening the corners or smoothing out wrinkles along the sides, only a small amount of metal should be left in the corners.

Frequently, it is necessary to draw shapes on dies designed to make a deeper single draw than is practical for the high-nickel materials. With such dies, the general practice is to draw about two-thirds of the full depth on the same dies. This same practice can be used to avoid wrinkling in drawing to lesser depths.

Spinning

Parts having a shape symmetrical about one axis may be formed by spinning when production volume is too small to justify the expense of deep-drawing dies. The blank may be a disc of sheet or plate, a length of tube, or a rough cone or cylinder preformed from sheet or plate by welding fabrication.

Deformation of a flat blank occurs partly by bending and partly by shear. With a conical or tubular blank, deformation may occur almost entirely through shear, and is sometimes referred to as shear spinning. In shear spinning, the diameter of the finished part will be nearly the same as the starting blank diameter. Forming may be accomplished by pulling the metal under the tip of the tool (shear in tension), in which case it is called backward spinning; or by pushing the metal in front of the tool (shear in compression), called forward spinning. Forming pressure may be applied by hand (manual spinning) or by a power-driven tool post such as in hydrospinning and power rolling.

Power spinning is the preferred method for use on the high-nickel alloys. This method not only provides the force necessary to deform the high-yield-strength materials, but also the steady feed needed for maximum and uniform work hardening. However, thin material, particularly of Nickel 200 and MONEL alloy 400, can be manually spun with no difficulty. A typical setup for manual spinning is illustrated in Figure 5.

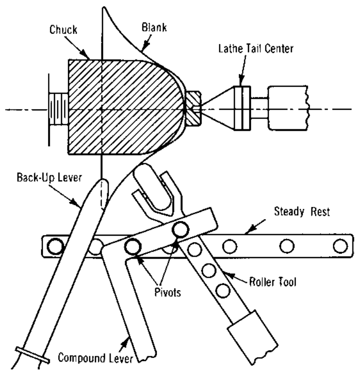

Figure 5. Typical equipment for manual spinning.

Table 6 indicates practical limits on blank thickness for manual spinning of several alloys.

Tools

Except for small, light shapes, the required pressure cannot be exerted with the ordinary bar or hand tool pivoted on a fixed pin. Most shapes require the use of a tool that is mechanically adapted for the application of greater force, such as a compound-lever tool or roller tools which are operated by a screw. For small jobs, a ball-bearing assembly can be used on the end of a compound lever to make a good roller tool. Roller tools should be used whenever practicable to minimize friction and maximize pressure. Roller tools should also be used to perfect the contour in the spinning of press-drawn shapes.

When possible, tools used for spinning the high-nickel alloys should be broader and flatter than those used for softer materials. The broader tool distributes plastic flow over a greater area and reduces overstraining. Except for this consideration, bar and roller tools for use on the nickel-alloy materials should be designed the same as those used for spinning copper. Some typical tools are shown in Figure 6.

Correct tool materials are essential for successful spinning. The most suitable material for bar tools is highly polished, hard-alloyed bronze. Hardened tool steels are preferred for roller and beading tools. Hard chromium-plated, hardened tool steel is recommended as it decreases metal pickup by the tool. Tools of common brass and carbon steel, which are used for spinning softer materials, are unsatisfactory for use with the high-nickel alloys.

Rotary cutting shears are preferred for edge trimming. If rotary shears are not available, hand trimming bars tipped with a hard-facing alloy may be used, but the trimming speed must be reduced. Hand trimming bars should be ground so that they have a back-rake angle of 15 to 20 degrees from the cutting edge, and the edge must be kept sharp. A tool shaped like a thread-cutting lathe tool can be used for trimming. This tool also has a back rake from the cutting edge. With this type of tool, the material is not sheared off the edge; the tool is fed into the side of the shape and a narrow ring is cut from the edge. The workpiece should be supported at the back during all trimming operations.

Table 6 — Maximum Blank Thickness and Hardness for Manual Spinning (Hand or Compound-Lever Tools)

Alloy	Maximum Hardness		Maximum Thickness	
	Rb	HV	in.	mm
Nickel 200	64	115	0.062	1.6
Nickel 201	55	100	0.078	2.0
MONEL alloy 400	68	122	0.050	1.3
INCONEL alloy 600	80	151	0.037	0.94
INCONEL alloy X-750	94	209	0.037	0.94

Chucks

Hard, nickel-chromium cast-iron and steel chucks give longer life and better results than wooden chucks. Hard maple or birch chucks may be used for intermediate operations in limited productions. Wooden chucks can be used for finishing if the production run is short and if tolerances are liberal. A metal chuck should be used for the final shaping to permit the removal of tool marks from previous operations against wooden chucks and to reduce the time required for polishing the article. Metal chucks must be used if a smooth finish and close tolerances are required.

Spinning the high-nickel alloys over chucks that are the same as those used for copper will not necessarily result in spun shapes of exactly the same dimensions as those of the softer material. In most cases, shapes of the high-nickel materials will have slightly larger peripheries than those of the softer materials spun over the same chuck. The cause is a difference in springback resulting from higher yield strengths and work-hardening rates of the nickel alloys.

Lubricants

Heavy-bodied, solid lubricants, such as soap, beeswax, and tallow, are recommended for spinning. These lubricants can be manually applied to the blank as it rotates. Blanks can be electroplated with 0.0002 to 0.0007 in. (0.005 to 0.018 mm) of copper to improve lubrication on difficult shapes.

Procedure

The procedure for spinning the nickel alloys is essentially the same as that used for other metals. The work should be laid down firmly on the chuck with long, powerful strokes. The material should not be crowded, and reworking a

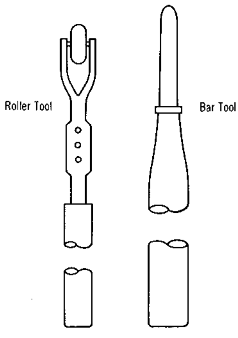

Figure 6. Tools for manual spinning.

surface should be avoided. As soon as the metal ceases to flow, spinning should be stopped. The article should then be trimmed and annealed in preparation for the next operation. If spinning is carried too far, the overstrained material will develop numerous small surface cracks. Such material cannot be restored by either annealing or burnishing.

As a general rule in laying out a spinning sequence for MONEL alloy 400, an increase in height of 1 to 1½ in. (25 to 38 mm) on the article being spun constitutes an operation if spinning is being done with the usual bar tool. Approximately twice that depth per operation may be obtained with a compound-lever or roller tool. The shape should be trimmed and annealed before it is spun to greater depths.

Shapes of Nickel 200 and Nickel 201, in the early stages of spinning, can usually be spun to two and occasionally three times the depth of a shape in MONEL alloy 400 before annealing is required. The judgment of the spinner is important in determining whether another operation will result in overstraining the material.

A hard-surfaced chuck should be provided for each operation so that the metal can always be pushed firmly against its surface. This procedure keeps the surface of the work smooth and dense, ensuring the best results in annealing. With an insufficient number of intermediate chucks, the material is subjected to an excessive amount of cold working. This may result either in spinning a buckle into the material or in pulling it and forming a pebbled surface. It is practically impossible to smooth out the former by additional cold work, or to correct the latter by annealing.

Figure 7 illustrates the number of chucks and annealing operations necessary to spin deep cups from 0.037-in. (0.94mm) thick blanks of Nickel 200, MONEL alloy 400, and INCONEL alloy 600 using hand tools. This figure also shows the amount of forming that can be done before annealing and between intermediate anneals. The spinnability of other alloys may be estimated from their relative work-hardening rates shown in Figure 1, and from their tensile properties shown in the Appendix.

In the spinning, the optimum speed of the rotating blank is governed by its diameter and thickness. Small, thin blanks can be spun at greater speeds than larger or thicker pieces. Most operators spin the high-nickel materials at speeds of one-half to three-fourths those normally used in spinning the same shape from the softer metals. Lathe speeds from 250 to 1000 rpm are usually satisfactory. Trimming speeds must necessarily be slow; the minimum speed of the lathe is usually used.

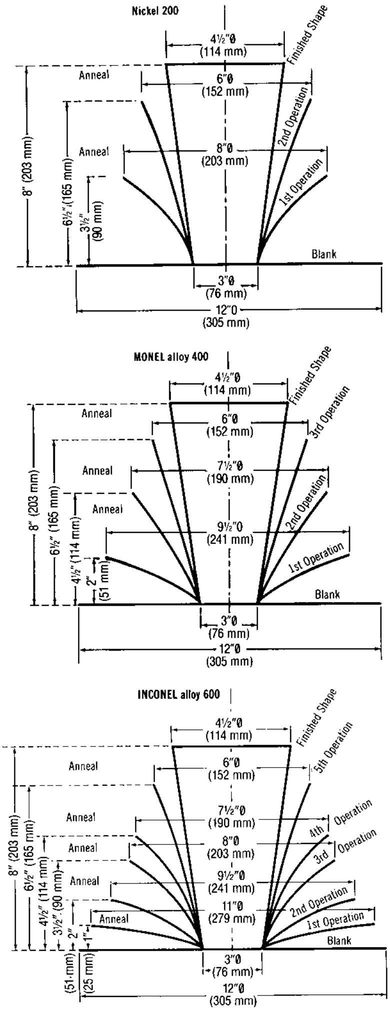

Figure 7. Sequence of operations for spinning deep cups from 0.037 in. (0.94mm) thick blanks of Nickel 200, MONEL alloy 400 and INCONEL alloy 600.

Forming of tube and pipe

All common forming operations such as bending, coiling, and expanding can readily be performed on tube and pipe of the SMC alloys. In general, material in the annealed condition is recommended. MONEL alloy 400, Nickel 200 and Nickel 201 can be formed in the stress-relieved temper. However, the amount of deformation will be limited by the higher tensile strength and lower ductility. In bending, the minimum radius to which stress-relieved tubing can be bent is 25 to 50% greater than for annealed tubing of the same size.

Bending and Coiling

Standard methods of bending are ram or press bending, roll bending, stationary-die bending, and rotating-die bending. Tubing and pipe of the Inco alloys are readily bent by any of these procedures.

An important precaution to observe in all bending is to allow maximum radii to ensure that applied stresses are as evenly distributed as possible. The minimum radii to which nickel alloy tubing can be bent by various methods are given in Table 7. This table should be used as a guide to general limitations. Depending on equipment design, tube size, and quality of the finished bend, it is possible to bend to smaller radii than those listed. However, when smaller radii are necessary, trial bends should be made to determine if the desired bend is possible.

Bending Without Mandrels or Fillers

In bending with no internal support, the dies should be slightly smaller than those used for bending with a mandrel or filler. Bending without use of a mandrel or filler is suitable only for tube and pipe that have a wall thickness greater than 7% of the outside diameter, or for bends of large radii. Nickel-alloy tube in sizes within the above ratio can be bent with no mandrel or filler to a minimum mean radius of three times the outside diameter of the tube (3D) through 180 degrees.

Table 7 — Minimum Bend Radii

Method of Bending	Minimum Mean Bend Radius	Maximum Included Angle of Bend, degrees
Press Bending, Unfilled Tube	6D[a]	120
Roll Bending, Filled Tube	4D	360
Stationary Die, Unfilled Tube	2½D	180
Stationary Die, Filled Tube or Using Mandrel	2D	180
Rotating Die, Unfilled Tube	3D	180
Rotating Die, Filled Tube or Using Mandrel	2D	180

[a] D=outside diameter of tube.

Bending With Mandrels or Fillers

Thin-wall tubing may be bent to small radii without wrinkling by use of a mandrel or filler. Thin-wall tubing of the high-nickel alloys may be mandrel-bent through 180 degrees to a minimum mean radius of 2D.

To minimize galling of the inside surface of the tube, mandrels should be made of hard alloy bronze rather than steel. Steel mandrels may be used but should be chromium plated to reduce galling.

Mandrels must be lubricated before use. Lubricants of extreme-pressure, chlorinated oil are best for severe bending. For less severe bending or for ease of removal, water-soluble lubricants are used.

Any of the standard filler materials such as sand, resin, and low-melting-point alloys may be used. Sand is the least desirable because it is difficult to pack tightly and hence can lead to the formation of wrinkles or kinks during bending.

Low-melting-alloy fillers produce the best bends. The expansion characteristics of these alloy fillers ensure that voids are eliminated and a sound center is created.

Alloy fillers are removed by heating the bent tube in steam or hot water. Metallic fillers must not be removed by direct torch heating since they contain elements such as lead, tin, and bismuth which will embrittle the high-nickel alloys at elevated temperatures. It is imperative that all traces of metallic fillers be removed if the tube will be subjected to elevated temperatures during subsequent fabrication or during service.

Press Bending

Press or ram bending, in which the tube is held by two supporting dies and a force is applied between the dies (see Figure 8), is normally used only for heavy-wall tubing where some flattening is tolerable. This method does not provide close tolerances and is applicable only to large-radius bends. The bend is limited to 120 degrees, and the radius of the bend should not be less than

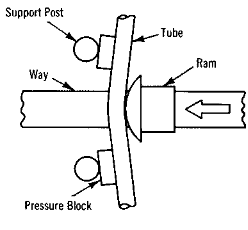

Figure 8. Equipment for press bending.

six times the outside diameter of the tube (6D) if a smooth bend is desired. A filler material should be used if bends of radii less than 6D are to be made.

Pressure blocks used in press bending should be at least two times the outside diameter of the tube in length. Press bending with wing dies is used for unfilled, thin-wall, large-diameter tube.

Annealed tubing is not always preferred for press bending. Annealed tubing of low base hardness does not possess sufficient stiffness to withstand deformation without excessive flattening. Consequently, Nickel and the MONEL nickel-copper alloys are usually press bent in the stress-relieved temper. The chromium-containing INCOLOY, NIMONIC, and INCONEL alloys have higher mechanical properties in the annealed condition than the nickel and nickel-copper alloys and should be press-bent in the annealed temper. Ideally, the choice of temper for a specific bend is determined from the results of several trial bends.

Roll Bending

Roll bending (Figure 9) is the principal method of producing helical coils, spirals, and circular configurations since an included angle of 360 degrees can be obtained. Bending may be done on either unfilled or filled tube. The minimum bend radius for unfilled tube is approximately six times the outside diameter of the tube.

Stationary-Die Bending

Stationary-die bending (Figure 10) utilizes a stationary bending die and a movable pressure die. This method is not suitable for thin-wall tubing and is generally used with no mandrel support.

Stationary-die bending can produce bend radii down to 2½ D but is normally used only for large-radius bends. The maximum included angle that can be produced is 180 degrees.

Rotating-Die Bending

Rotating-die bending is the most common bending process and is the preferred method for bending nickel-alloy tube. The process is similar to stationary-die bending except that the bending die revolves and the wiper block remains stationary.

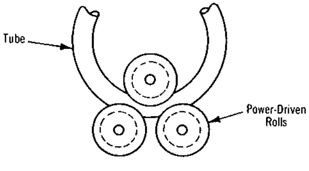

Figure 9. Roll bending. The bend radius is controlled by raising or lowering the top roll.

Rotating-die bending machines may have either a fixed wiper block (Figure 11) or a sliding wiper block (Figure 12). The sliding wiper block is preferred because it distributes the applied stresses more evenly.

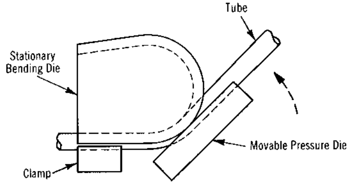

Figure 10. Stationary-die bending.

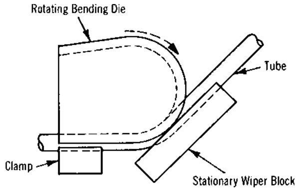

Figure 11. Rotating-die bending with stationary wiper block.

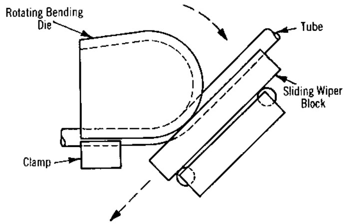

Figure 12. Rotating-die bending with sliding wiper block.

Tubing can be bent as much as 180 degrees with a minimum radius of 2D by rotary bending. Although bending can be done without a mandrel, a mandrel is generally preferred and must be used when the ratio of tube diameter to wall thickness is above the limit suitable for bending without wrinkling or collapsing of the tube. Various types of mandrels are used including ball and straight-plug types.

Expanding Heat-Exchanger Tube

Tubing of the SMC alloys can be expanded into tube sheets by any conventional method. Some design factors which must be taken into consideration in expanding or rolling tubing include thickness of the tube sheet, wall thickness of the tube, tube spacing or ligament between tube-sheet holes, rolling practice, clearance between tube and hole, and the relative hardnesses of the tube and tube sheet. If an unfamiliar design is being used, trial tests should be performed to determine if difficulties may be encountered in expanding.

The oversize allowance on tube-sheet holes to the nominal outside diameter of the tube should be kept to a minimum. The tube-sheet hole should be 0.004 to 0.008 in. (0.10 to 0.20 mm) larger than the nominal outside diameter of the tube for tubing less than 1½ in. (38 mm) O.D. For larger tubing the oversize-allowance should be 0.009 to 0.010 in. (0.23 to 0.25 mm).

Procedure

Expanding may be done by drifting with sectional expanders or by rolling with three-roll expanders. Three-roll expanders are preferred. The ends of rolled-in tubing are flared in the conventional manner.

The tube-sheet hole and both the outside and inside surfaces of the tube must be free of all matter such as oxide, dirt, and oil. The ends of the tube should also be deburred before rolling.

Lubrication should be provided between the rollers of the tool and the inside surface of the tube. Any sulfur-free mineral oil or lard oil, either diluted or straight, may be used. Lubricants that contain embrittling or contaminating elements such as sulfur or lead should be avoided because of the difficulty in cleaning the finished assembly.

Controlled rolling equipment should be used to prevent over-expanding the tubes. Over-expanding may distort the tube sheet and plastically deform the tube-sheet ligaments, causing loose-fitting tubes. This is particularly true when the tube has a higher hardness than the tube sheet or a significantly higher work-hardening rate.

Material Temper

The tube sheet should be harder than the tube being rolled into it. Otherwise, springback in the tube may be greater than in the tube sheet, causing a gap between the two when the expanding tool is removed. For that reason, tube sheets are usually supplied in the as-rolled or as-forged temper and tube in the annealed temper. It is particularly important for the tube sheet to be harder than the tube when the sheet is thinner than the outside diameter of the tube or when the tubes are closely spaced. Tubes are closely spaced when the tube-sheet ligament is less than the greater of 25% of the outside diameter or ¼ in. (6 mm).

Stress-relieved tubing may be slightly harder than the tube sheet but can be expanded to form a satisfactory connection if greater care is exercised in expanding. For greater assurance of pressure tightness, a seal weld may be placed around the end of the tube after expanding. The stress-relieved temper is suitable for either welding or silver brazing.

If rolling of stress-relieved tube appears to be a marginal operation, the problem can often be remedied by using annealed tube or stress-relieved tube with the ends annealed. Stress-relieved, end-annealed tubing combines the strength advantage of stress-relieved material with the ease of fabrication of annealed material.

Tubing in the annealed condition is used when optimum rolling or expanding characteristics are desired or when severe cold-bending and flaring are to be done.

Miscellaneous Forming Operations

Flanging, bulging, swaging, and other expanding or reducing operations can be readily performed on tube and pipe of the high-nickel alloys. Many such operations are variations of those discussed in this section, and comments made on specific operations will also apply to the variations.

Extremely severe or complex forming operations may require that the material be given one or more intermediate anneals to prevent rupturing from excessive cold work.

Forming of rod and bar

In general, rod and bar in the annealed condition are preferred for cold forming. Material in other tempers may be required for some forming operations or when properties that cannot be obtained by heat treatment after forming are desired in the end product.

Bending and Coiling

Rod and bar may be bent in the same manner as tubing. The possibility of collapsing or wrinkling is eliminated since the solid section provides its own internal support. If failure occurs during bending, it will usually appear as cracking or tensile rupturing on the outside radius of the bend. This type of failure occurs when the bend radius is too short. The minimum radius to which rod and bar can be bent is a function of the diameter or thickness of the material. Shorter bend radii can be produced on small-diameter rod and thin bar than on larger or thicker material.

Small sizes are often bent manually on a pinned block, sometimes with the aid of a lever arm, and with no lubricant. Three-roll benders and press brakes are also used to bend small sizes. Bending by these methods may be done dry or with mineral-oil lubricant.

Large sizes may be bent on a hydraulic punch press, a large press brake, or a pinned block with a block-and-tackle arrangement. High-speed rod benders similar to tube-bending machines are used for large production volumes.

Since stresses developed in bending rod and bar are almost entirely in the longitudinal direction, longitudinal surface imperfections normally associated with hot-rolled products do not cause serious difficulty. Hot-finished products can often be bent without any special surface conditioning.

Most of the nickel alloys have suitable mechanical properties in the hot-finished condition for moderate bending. Annealed temper should always be used for extremely short bend radii or low radius-to-thickness ratios. Cold-drawn, annealed material should be used if surface roughening (orange peeling) related to coarse grain structure is undesirable.

Coiling of rod and bar is limited almost entirely to the production of springs. Coil springs are produced from rods and, occasionally, from squares.

Springs of the high-nickel alloys that are intended for high-temperature service are usually annealed or solution treated and age hardened after forming. Consequently, these springs may be produced from annealed material (or even produced by hot coiling) with no adverse effect on final properties.

If the desired properties cannot be obtained by heat treating after forming, the spring must be coiled from tempered, cold-worked material. The use of tempered material will greatly increase the minimum radius to which the rod or bar may be coiled.

Pressures and speeds encountered in production coiling usually require the use of high-grade lubricants with good film strength. Wire rod is often coated with copper to reduce friction and to improve retention of organic lubricants.

The severe cold-forming involved in producing coils as well as the severe service conditions in which these products are often used demands starting material with high surface quality. Centerless-ground or ground and cold-drawn material is used to obtain the necessary quality.

Cold Heading and Extrusion

Cold heading and extrusion are most often used in the production of fasteners and similar cold-upset parts. Cold extrusion of the high-nickel alloys is rarely done except in conjunction with cold heading.

The high strength and galling characteristics of the nickel alloys require slow operating speeds and high-alloy die materials. Cold-heading machines should be operated at a ram speed of about 35 to 50 fpm (10 to 15 m/min). These ram speeds correspond to operating speeds of 60 to 100 strokes per minute on medium-sized equipment.

Tools should be made of oil- or air-hardening die steel. The air-hardening types, such as D-2, D-4, or high-speed steel (M-2 or T-1) tempered to a hardness of 60 to 63 Rockwell C, are preferred.

Material

Rod stock (usually under 1-in. (25 mm) in diameter) in coils is used for starting material since cold heading is done on high-speed, automatic, or semi-automatic equipment. Although MONEL alloy 400 is sometimes cold-headed in larger sizes, ⅞ in. (22 mm) is the maximum diameter in which MONEL alloys 400 and K-500 can be cold-headed by most equipment. The limiting sizes in harder alloys are proportionally smaller, depending on their hardness and yield strength in the annealed condition. Larger sizes are normally hot-headed by practices essentially the same as other forging operations covered in the hot-forming section of this bulletin.

Cold-heading equipment requires wire rod with diameter tolerances in the range of ±0.003 to 0.005 in. (0.08 to 0.13 mm). Since MONEL alloy 400 should be cold-headed in 0 to No. 1 temper for resistance to buckling during forming, these tolerances can normally be obtained with the drawing pass used to develop the temper. For tighter tolerances or harder alloys, fully cold-drawn and annealed material must be used.

The surface quality of regular hot-rolled wire rod, even with a cold sizing pass, may not be adequate for cold heading. Configurations that are especially prone to splitting, such as rivets, flat-head screws, and socket-head bolts, require shaved or centerless-ground material.

Lubricants

To prevent galling, high-grade lubricants must be used in cold heading the nickel alloys.

Lime and soap are usually used as a base coating on MONEL alloy 400. Better finish and die life can be obtained by using copper plating 0.0003 to 0.0007 in. (0.008 to 0.18 mm) thick as a lubricant carrier. Copper plating may also be used on the chromium-containing alloys such as INCONEL alloy 600 and INCOLOY alloy 800 but oxalate coatings serve as an adequate substitute.

Regardless of the type of carrier, a base lubricant is best applied by drawing it on with a light sizing pass to obtain a dry film of the lubricant. Any of the high-titer, dry soap powders containing sodium, calcium, or aluminum stearate can readily be applied in this manner.

If the wire rod is to be given a sizing or tempering pass before the cold-heading operations, the heading lubricant should be applied during drawing.

Lubrication for cold heading is completed by dripping a heavy, sulfurized mineral oil or a sulfurized and chlorinated paraffin on the blank as it passes through the stations of the heading operation.

Thread Rolling

In the manufacture of fasteners, threads are often produced by rolling the rod stock between rotating cylindrical dies or reciprocating flat dies. Either of these methods may be used on the high-nickel alloys.

To obtain maximum die life, material should be rolled in the annealed condition. Hot-finished or age-hardened material can be used to reduce heat-treating costs or to develop maximum tensile properties in the thread roots.

Occasionally, thread rolling, especially with flat reciprocating dies, will develop sheer stresses at the center of the rod that are sufficient to cause internal rupturing of the workpiece. This can be prevented by reducing the blank diameter, increasing the die clearance or by rolling in two or more passes to reduce the stress level. If none of these is feasible, it may be necessary to select material that is more resistant to internal rupturing.

Straightening

Rod and bar in straight lengths are usually straightened by conical rolls, stretchers, or punch presses. Material in coil form is straightened with one- and two-plane staggered-roll straighteners or rotating-die straighteners.

Like other forming equipment, straighteners require about 50% more power for high-nickel alloys than for mild steel; a straightener having a capacity of ½-in. (13-mm) diameter in steel will be limited to about ⅜-in. (10-mm) diameter in the nickel alloys. A lubricant should be used with rotating-die straighteners to reduce scratching and scoring, and to improve die life. Spiral scoring may become quite severe on large sizes of harder alloys. If scoring cannot be held to an acceptable level by using lubricants, material in the softest available temper should be used.

Staggered-roll straightening involves lower contact velocities than rotating-die methods, and lubrication is less critical. Coil stock is often straightened without a lubricant to provide a better grip on the rolls.

Dies for rotary-die straighteners may be either bronze or cast iron. Cast-iron dies must be used where contamination from bronze rubs might occur in the end product and no pickling is done after straightening.

Cold-formed parts for high-temperature service

A part that is highly stressed by cold forming may require heat treatment to avoid excessive creep during subsequent exposure above the recrystallization temperature. Recrystallization, in a particular alloy, is determined largely by the extent of cold working and the temperature at which the part is exposed in service. In addition, the grain size and exact composition of the material as well as the time at temperature complicate the prediction of the recrystallization temperature.

The SMC alloys most likely to be subjected to temperatures above the recrystallization temperature are the INCOLOY nickel-iron-chromium alloys and the INCONEL and NIMONIC nickel-chromium alloys. Those alloys are frequently used in the grain-coarsened condition where temperatures exceed 1100°F (595°C).

Generally, cold-formed nickel alloys should be heat treated if they have been strained either in tension or compression by more than 10% and will be subjected to temperatures above 1200°F (650°C). For the recommended heat treatments, consult Special Metals Corporation

For an application such as return bends for chemical and petrochemical processes, tubing should be fabricated in the cold-finished, annealed condition. Hot-finished tubing should be fabricated as hot-finished or in the hot-finished, annealed condition. If the operating temperature is 1200°F (650°C) or higher, the bend should then be heat treated according to the procedure obtained by consulting Inco Alloys International. Bends in INCOLOY alloy 800HT tubing have undergone recrystallization in tests where the radius is smaller than four times the diameter. Test bends are required to determine the minimum bend radius at which a given material can be put into service without heat treatment.

In certain materials, heavy cold working, as in highly restrained bending, followed by exposure at moderate to elevated temperatures, as in stress relieving or age hardening, can lead to cracking. In age-hardenable alloys, for example, the combination of high residual tensile stress and the stress associated with the aging response may exceed the stress-rupture strength of the material. In non-age-hardenable alloys of the INCOLOY and INCONEL families, excessive cold working of coarse-grained material (i.e., grain size of ASTM No. 5 or coarser) without the recommended intermediate annealing can cause cracking during subsequent exposure at stress-relieving or annealing temperatures. Tests of the material under the actual conditions of forming and heating will determine its susceptibility to cracking.

Springs can be cold formed from age-hardenable alloys in the annealed or cold-drawn temper. For service temperatures above about 600°F (300°C), springs should be solution annealed before aging to prevent loss of strength from relaxation.

Introduction

General procedures for heating the SMC alloys are described in this section. These procedures apply to all of the alloys except where otherwise noted. More specific information concerning the heating of individual alloys is contained in the bulletins pertaining to those alloys.

Prevention of contamination

Nickel and nickel alloys are susceptible to embrittlement (diseasing) by sulfur, phosphorus, lead, zinc, and some other low-melting-point metals and alloys. These materials may be present in lubricants, paints, marking crayons and inks, pickling liquids, dirt accumulated on metal during storage, furnace slag and cinder, or temperature-indicating sticks, pellets, and lacquers. Any foreign substances, even those that are nonembrittling, can burn into the surface of metal at high temperatures and cause difficulty in later processing. In addition, vapors produced when the substances burn are usually objectionable and can have an adverse effect on furnace and heating fixtures. *It is therefore extremely important that the metal be cleaned before heating.* Careful cleaning results in a real operating economy by preventing damage to the material and by facilitating subsequent operations.

The importance of proper cleaning before heating is illustrated in Figure 13. This sample of INCONEL alloy 600 was not cleaned to remove a sulfur deposit from the surface before being heated. The damage caused by sulfur attack at the heating temperature is evident in the photomicrograph of the metal's cross section.

Processes for cleaning the nickel alloys are the same as for other metals. Soaps can be removed with hot water. Soluble oils, tallows, fats, and fatty acid combinations can be removed with a hot (180° to 200°F, 80° to 90°C) alkaline solution of 10 to 20% sodium carbonate (soda ash) and 10 to 20% trisodium phosphate in water. Sodium hydroxide (caustic soda) may be used instead of sodium carbonate. Such alkaline compounds are potentially hazardous to the skin and eyes and should be used carefully. Parts should be immersed in the solution for 10 to 30 minutes and then thoroughly rinsed in water. If sodium carbonate residues remain on the metal after rinsing, they must be removed by scrubbing with hot water.

Mineral oils and greases can be removed with various solvents. The remaining film should be removed from the surface by the previously mentioned alkaline cleaner. Vapor-degreasing machines work well for removing mineral oils and greases.

Paint can be removed with alkaline cleaners or special proprietary compounds. Marking ink can usually be removed with alcohol.

All solvents and cleaners must be used according to the manufacturers' safety precautions.

In addition to being cleaned before heating, the metal must be protected while in the furnace. To avoid contamination, nickel alloys should not be placed on refractory hearths. They should be placed instead on metal floors or rider bars or held in metal baskets, boxes, or trays. If necessary, protective metal covers should be used to prevent roof spallings from falling onto the work.

Fuels

Either electricity or various gases and fuel oils can be used for heating. Gases and oils should be carefully selected. A low sulfur content is an important requirement for any fuel.

Coal and coke are usually unsatisfactory for heating high-nickel alloys because of the difficulty in providing proper heating conditions, inflexibility in heat control, and excessive sulfur content.

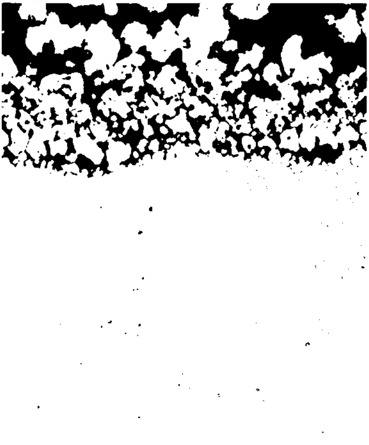

Figure 13. Photomicrograph (100X) of the cross section of a sample of INCONEL alloy 600 having a sulfur deposit on the surface and heated to a high temperature. Gray areas at the center show sulfidation; dark areas at the top show extreme oxidation that rapidly follows sulfidation. (Unetched).

Gas

Gaseous fuels are the best fuels for heating high-nickel alloys and should always be used if available. Good heating is readily achieved with these fuels because they mix easily with air and their supply is easily controlled. Gaseous fuels require only a small amount of combustion space, and furnace atmosphere and temperature can be controlled by automatic equipment.

Natural gas, primarily consisting of methane and smaller amounts of ethane, propane, and butane, and essentially free of sulfur compounds, is available in many localities.

Manufactured gases are produced from coal or oil which may contain substantial amounts of sulfur. These gases should not be used unless sulfur compounds are reduced to an acceptable level during manufacture. Sulfur occurs in manufactured gases as hydrogen sulfide and as organic sulfides.

The regulations of many states in the U.S.A. require that manufactured gas must not contain more than 30 grains of total sulfur per 100 cubic feet (690 milligrams per cubic metre) of gas. The sulfur content may vary considerably from day to day, but, if adequate sulfur-removal procedures are followed during manufacture, the total sulfur content will average 10 to 15 grains per 100 cubic feet (230 to 345 milligrams per cubic metre) of gas or lower. This amount of sulfur is acceptable for heating high-nickel alloys; however, the generally accepted statutory limit of 30 grains per 100 cubic feet (690 milligrams per cubic metre) is marginal.

Butane and propane, components of natural gas that liquefy and separate out when the gas is compressed, give good results in heating. Both fuels are stored and shipped in tank cars of large capacity—up to 15 000 gallons (57 cubic metres)—and may be distributed in pipe lines under their own vapor pressures.

Butane, which can be considered as an oil fuel of high volatility, must be gasified by heating before it is mixed with air for combustion.

Propane is more volatile and does not require heating to convert it from liquid to gas. Propane is also available in cylinders equipped with pressure regulators. These cylinders are useful for occasional heating of small parts.

Oil

Oil is a satisfactory fuel provided it has a low sulfur content. Oil for heating nickel alloys should not contain more than 0.5% by weight of sulfur. This is the equivalent of an ASTM Grade 1 fuel oil.[1] If the use of a high-sulfur fuel oil is unavoidable, the furnace atmosphere should be adjusted to be slightly oxidizing. Although a reducing atmosphere is normally preferred, sulfur is less harmful in the oxidized state.

Any good burner that will mix the oil and air supply thoroughly, and that can be regulated closely, will be satisfactory. Burners having low-pressure air supplied through the burner are superior to high-pressure or steam-injector types. Low-pressure burners work well with automatic temperature-control equipment.

Heating methods

The two most important methods of heating are open heating and closed or box heating. A third method, salt-bath heating, is used for special work with small parts.

Open Heating

In open heating, the material is charged directly into the furnace and heated at the selected temperature for the desired time. This method is widely used in heating for mechanical properties and is the usual method in heating for hot working.

Furnaces are heated by fuel-oil or gas burners, gas-fired radiant tubes, or electric resistance elements. A protective atmosphere is usually provided. Continuous furnaces equipped with seals, controlled atmospheres, and protected cooling zones are often used for bright annealing. Oil- or gas-burning, directly fired furnaces are usually used in heating for hot working. Batch furnaces are normally used for age hardening because of the long-time cycles required.

Closed Heating

In closed or box heating, the work is placed in a container which is then sealed and charged into the furnace. Although both annealing and hardening can be accomplished by closed heating, this method is more appropriate for hardening.

Box annealing is usually carried out at lower temperatures than open annealing, and longer times are required. The box must be heated to a slightly higher temperature than that required for the work. In most cases, the weight of the container exceeds the weight of the work. Therefore, the amount of heat required for closed annealing is considerably greater than for open annealing.

In general, none of the chromium-containing alloys such as INCONEL alloy 600 and INCOLOY alloy 800, nor any of the precipitation-hardenable alloys, should be boxed-annealed unless a means of high-speed convection cooling is provided. Forced cooling and a protective atmosphere are necessary to prevent oxidation on chromium-containing alloys and to prevent hardening of precipitation-hardenable alloys.

As in all heating of the high-nickel alloys, cleanliness is important. To avoid contamination, the boxes must be clean and free from rust and loose scale.

A gas-tight thermocouple well should be positioned in the box so that the hot junction of the thermocouple will be in the approximate center of the charge.

A suitable atmosphere must be maintained within the box throughout the complete cycle of treatment.

Salt-Bath Heating

The SMC alloys can be heated in salt baths to prevent excessive oxidation. However, equivalent results can normally be achieved by using an appropriate furnace atmosphere. Salt-bath heating is applicable to small parts only.

Baths are composed of inorganic salts such as chlorides and carbonates of sodium and potassium, which are relatively stable at temperatures considerably above their melting points. The salts are melted, or fused, in pots by any convenient source of heat. The maximum usable temperature of the bath is indicated by excessive fuming.

To prevent embrittlement of the work, all traces of sulfur must be removed from the fused salts before use. That may be accomplished in 2 to 3 hours by adding a small amount of a mixture of three parts (by volume) powdered borax and one part powdered charcoal to the fused salts. If small test pieces of Nickel 200 or MONEL alloy 400 strip or wire are not embrittled after heating for 3 to 4 hours in the purified salt bath, the desulfurizing treatment has been sufficient.

Heat treating is accomplished by placing the material in the molten salts, where it absorbs heat rapidly. After heating, the work is washed in water to remove particles of the salt mixture. The heat-treated material must be pickled if bright surfaces are required.

Protective atmospheres

High-nickel alloys are subject to surface oxidation unless heating is performed in a protective atmosphere or in a vacuum. A protective atmosphere can be provided either by controlling the ratio of fuel and air to minimize oxidation or by surrounding the metal being heated with a prepared atmosphere.

MONEL alloy 400, Nickel 200, and similar alloys will remain bright and free from discoloration when heated and cooled in a reducing atmosphere formed by the products of combustion. The alloys that contain chromium, aluminum, or titanium form thin oxide films in an atmosphere formed by combustion products and require prepared atmospheres to maintain bright surfaces.

Regardless of the type of atmosphere used, it must be sulfur-free. Exposure of nickel alloys to sulfur-containing atmospheres at high temperatures can cause severe damage to metal. Figure 14 shows the effects of heating INCONEL alloy 600 in a high-sulfur atmosphere.

The atmosphere of concern is that in the immediate vicinity of the work, that is, the combustion gases which actually contact the surface of the metal. The true condition of the atmosphere is determined by analyzing gas samples taken at various points about the metal surface.

Furnace atmospheres can be checked for excessive sulfur by heating a small test piece of the material to be heated, for example, ½-in.-(13 mm) diameter rod or ½ in. × 1 in. (13 mm × 25 mm) flat bar, to the required temperature and holding it at temperature for 10 to 15 min. The piece is then air cooled or water quenched and bent through 180 degrees flat on itself. If heating conditions are correct, there will be no evidence of cracking.

Reducing Atmosphere

The most common protective atmosphere used in heating the SMC alloys is that provided by controlling the ratio between the fuel and air supplied to the burners. A suitable reducing condition can be obtained by using a slight excess of fuel so that the products of combustion contain at least 4%, preferably 6%, of carbon monoxide plus hydrogen. The atmosphere should not be permitted to alternate from reducing to oxidizing.

An Orsat gas analysis will show whether or not the content of carbon monoxide is in the proper proportion with that of the other components of the atmosphere. Other analytical techniques using commercially available instruments show percentages of combustible or excess fuel.

Excessive carbon monoxide, which carburizes steels but not most high-nickel alloys, nevertheless indicates a rich air-to-fuel ratio. Only a slight excess of fuel over air is needed.

Figure 14. Sulfidation of INCONEL alloy 600 caused by heating in a high-sulfur atmosphere.

The stack dampers should be controlled to maintain a slight positive pressure in the furnace. Closing the dampers forces the gases out around the furnace door, where the combustibles (carbon monoxide and hydrogen) burn freely, and prevents air from entering around the door or through the slot. Thus, control of the dampers helps to achieve uniformity of temperature throughout the furnace.

It is important that combustion takes place before the mixture of fuel and air comes in contact with the work; otherwise the metal may be embrittled. To ensure proper combustion, ample space should be provided to burn the fuel completely before the hot gases contact the work. Direct impingement of the flame can cause cracking.

In slot-type furnaces with oil burners in the back or end walls, both combustion and heating are done in the space above the hearth. In many installations the space is not large enough for proper combustion of fuel oil. In such furnaces, a large portion of the fuel oil is gasified by impingement on the hot metal. That places the work directly in the combustion zone and may cause overheating and embrittlement from incipient fusion. If possible, the furnaces should be modified by setting the burners back and firing through a tunnel, or by tilting the burners so that the flame is directed against the roof and opposite wall. If the furnaces cannot be changed, the work must be shielded with alloy plates or a refractory or metallic muffle to prevent unburned fuel from contacting the hot metal.

Prepared atmosphere

Various prepared atmospheres can be introduced into the heating and cooling chambers of furnaces to prevent oxidation of nickel alloys. Although these atmospheres can be added to the products of combustion in a directly fired furnace, they are more commonly used with indirectly heated equipment. Prepared protective atmospheres suitable for use with the alloys include dried hydrogen, dried nitrogen, dried argon or any other inert gas, dissociated ammonia, and cracked or partially reacted natural gas. For the protection of pure nickel and the MONEL nickel-copper alloys, cracked natural gas should be limited to a dew point of 30° to 40°F (−1° to 4°C).

Properties of some protective atmospheres are given in Table 8. Nickel 200, MONEL alloy 400, and similar alloys that do not contain chromium can be bright-heated in all of these atmospheres. INCONEL alloy 600 and other chromium-containing alloys require completely dissociated ammonia (No. 4 in Table 8) or hydrogen (No. 6) to maintain bright surfaces. Chromium-containing alloys such as INCONEL alloy 625 and INCOLOY alloy 800 which are prone to nitriding require an atmosphere of 100% hydrogen.

Dissociated ammonia or hydrogen must be dry to prevent oxidation. Figure 15 illustrates the dew-point levels required.[2] In this figure, metal/metal oxide equilibria in hydrogen atmospheres are shown as functions of temperature and dew point. The area on the left of each curve is the oxidized condition and the area on the right is the reduced (bright) condition.

Figure 15 indicates that at a temperature of 2000°F (1095°C), a dew point of less than −20°F (−30°C) is required to reduce chromium oxide to chromium; at 1500°F (815°C) the dew point must

Table 8 —Protective Furnace Atmospheres for High-Nickel Alloys

No.	Type	Characteristics	Air-to-Gas Ratio	Composition, volume %					Dew Point		Fuel Gas Required per 1000 ft³ (28 m³) of Atmosphere
				H_2	CO	CO_2	CH_4	N_2	°F	°C	
1	Partially Burned Fuel, Medium-Rich	Combustible, Reducing	6:1[a]	15.0	10.0	5.0	1.0	69.0	Saturated[b]	Saturated[b]	115 ft³ (3 m³)[c]
2	Reacted Fuel, Rich	Combustible, Strongly Reducing	3:1[a]	38.0	19.0	1.0	2.0	40.0	+70	+21	145 ft³[c] (4 m³)[c]
3	Partially Burned Fuel, Lean	Noncombustible, Slightly Reducing	10:1	2.5	3.2	10.5	0.0	83.8			
4	Dissociated Ammonia (Complete Dissociation)	Combustible, Strongly Reducing	No Air	75.0	0.0	0.0	0.0	25.0	-70 to -100	-57 to -73	22.2 lb[d] (10 kg)[d]
5	Dissociated Ammonia, Partially Burned	Combustible, Strongly Reducing	1.25:1[e]	15.0	0.0	0.0	0.0	85.0	Saturated[b]	Saturated[b]	15.0 lb[d] (7 kg)[d]
6	Dissociated Ammonia, Completely Burned	Noncombustible, Inert	1.80:1[e]	1.0	0.0	0.0	0.0	99.0	Saturated[b]	Saturated[b]	13.3 lb[d] (6 kg)[d]
7	Electrolytic Hydrogen, Dried by Alumina plus Molecular Sieve	Combustible, Strongly Reducing	No Air	100.0	0.0	0.0	0.0	0.0	-70 to -100	-57 to -73	

[a]This ratio is for natural gas containing nearly 100% methane. Use one-half of the listed ratio for high-hydrogen (550 Btu/ft³ (21 MJ/m³)) manufactured gas; 40% of the listed ratio for low-hydrogen, high-carbon-monoxide (450 Btu/ft³ (17 MJ/m³)) manufactured gas. Double the listed ratio for propane; triple for butane.

[b]Dew point depends on drying method.

[c]This volume is for high-methane natural gas, double for manufactured gases. Use one-half of the listed volume for propane, one-third for butane.

[d]Weight of liquid ammonia required.

[e]Ratio of air to dissociated ammonia.

be below -60°F (-50°C). The values were derived from the thermodynamic relationships of pure metals with their oxides at equilibrium, and can be used only as a guide to the behavior of complex alloys under non-equilibrium conditions. However, they have shown a close correlation with practical experience. For example, INCONEL alloy 600 and INCOLOY alloy 800 are successfully bright-annealed in hydrogen having a dew point of -30° to -40°F (-35° to -40°C).

As indicated by Figure 15, lower dew points are required as the temperature is lowered. To minimize oxidation during cooling, the chromium-containing alloys must be cooled rapidly in a protective atmosphere.

The protective atmosphere within the furnace box or muffle must be maintained at a positive pressure throughout heating and cooling. That is especially important when hydrogen or dissociated ammonia is used as the atmosphere. Air infiltration can cause serious fires or even violent explosions. The precaution also applies to the initial filling of boxes or muffles with the atmosphere. The containers must be thoroughly purged with an inert gas to remove all air before heating. Hydrogen forms explosive mixtures with air over a wide range of compositions.

Various methods are used to remove air from furnace boxes and muffles prior to admitting the atmosphere. One method consists of evacuating the container to a sufficiently low level and then filling it with the desired atmosphere to produce a positive pressure within. Another satisfactory method consists of passing nitrogen or an inert gas through the container until all air is removed. About five volume changes of the purging gas will be required. An oxygen analysis should be performed to verify removal of air.

After the air is removed and the atmosphere is admitted, a positive pressure must be maintained inside the box. The best method to regulate the gas pressure is to adjust the gas flow according to a manometer connected to the outlet tube.

An alternative method of regulating the pressure in the box is to light the gas escaping from the outlet tube. A flame length of 1 to 2 in. (25 to 50 mm) is required, and, to minimize gas consumption, the tube should be fitted with an orifice, jet, or valve. This method is less reliable than the manometer method and uses more gas.

After heating, the box may be cooled in the furnace or withdrawn and cooled in air. A method of rapid cooling such as forced convection is necessary to prevent oxidation of chromium-containing alloys. A positive gas pressure must be maintained during cooling. When the metal cools below 500°F (260°C), there will be no danger of oxidation. The gas flow can then be stopped

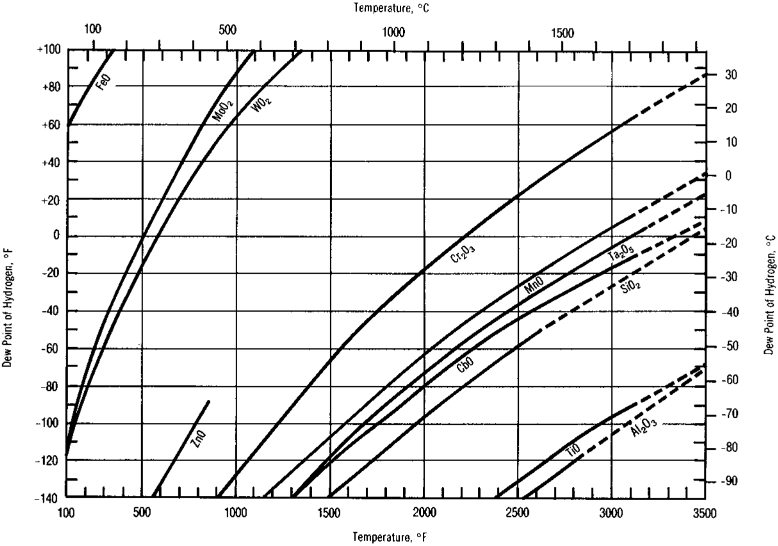

Figure 15. Metal/metal oxide equilibria in hydrogen atmospheres.[2]

and the metal removed. However, it is usually more convenient to allow the box to cool completely before removing the charge.

Gas generators

Two types of generators are commonly used to prepare protective atmospheres. One type partially reacts or burns fuel gases. The other type dissociates ammonia into its components, hydrogen and nitrogen.

Fuel-gas generators require careful control of the air-to-gas ratio. Figure 16 shows the various amounts of combustion products that can be obtained by reacting natural gas with air in a fuel-gas generator. This figure can also serve as a guide in controlling furnace atmospheres by adjusting the air-to-gas ratio of the mixture entering the burners.

Dew-point control

Water vapor decomposes into hydrogen and oxygen at high temperatures, particularly when catalyzed by hot metal surfaces. The oxygen produced is harmful in bright heating. Therefore, the water content of an atmosphere gas must be held to an acceptable level.

The dew point of a gas (the temperature to which it must be lowered to cause visible condensation) indicates its water-vapor or moisture content. Dew-point measurements must be made on samples of gas taken from inside the furnace. Water vapor can be introduced through moisture on the work or may leak in from the outside atmosphere. Therefore, the only dew point that has any significance is that of the gas in direct contact with the work.

Equipment for drying the gas should be located as close to the furnace as possible to minimize contact of hydrogen with rust deposits in pipe lines. Water vapor produced in the reduction of iron oxide raises the dew point of the gas. Pipe joints should be welded to avoid leaks.

High-purity hydrogen, which requires no drying, is available. It is produced from dissociated ammonia by palladium diffusion cells and contains virtually no water vapor or other impurities. Liquid hydrogen can also be used.

Temperature control

Accurate control of temperature is one of the most important factors in achieving good results in heating. Furnaces should be equipped with automatic temperature controls and maintained at the temperature that is recommended for the alloy being heated. Complete information concerning temperature measurement and control is available from manufacturers of pyrometric equipment.

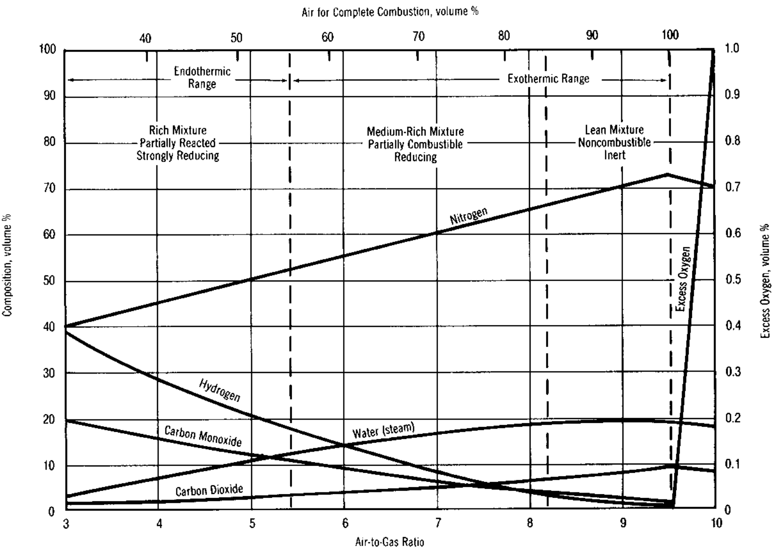

Figure 16. Characteristics and compositions of high-methane natural gas when reacted with air. (Compositions will vary slightly with different reaction environments. Also, small amounts of unreacted methane exist in the endothermic range.)

Thermocouples should be checked for accuracy at least once during each day of use. Thermocouples are subject to poisoning by various atmospheres and contaminants. Their accuracy can be impaired in a matter of minutes.

Cooling rate

The rate of cooling after heating is not critical for Nickel 200, MONEL alloy 400, or INCONEL alloy 625. After being heated for any purpose except age hardening, MONEL alloy K-500 and DURANICKEL alloy 301 should be water quenched not only to avoid excessive hardening and cracking that could occur if they were cooled slowly through the age-hardening range but also to maintain good response to subsequent aging. INCOLOY alloy 825 should be air cooled.

INCOLOY alloy 800 and INCONEL alloy 600 are subject to sensitization upon heating or slow cooling through the range of 1000° to 1400°F (540° to 760°C). If sensitization would be a problem in the end use, parts made of those alloys should be water quenched or cooled rapidly in air to avoid prolonged exposure in that range.

The precipitation-hardenable INCONEL and NIMONIC alloys should, in general, be cooled in air after being heated. Water quenching is not recommended, particularly for large sections or complex parts, because it can set up stresses that may cause thermal cracking during subsequent heating for further hot work or heat treatment.

For cooling after hot working, specific instructions are given in the procedures for the individual alloys on pages 28 through 31.

Quenching

All of the nickel alloys form an adherent oxide film if allowed to cool in air after heating. The film is difficult to remove and should be prevented if a bright surface is to be produced by subsequent pickling. When a cooling rate equal to air cooling is desired, the material should be cooled in a protective atmosphere. If rapid cooling is required, it should be done by high-speed convection under a protective atmosphere or by a reducing quench bath.

A suitable reducing quench can be provided by adding 2% (by volume) of either ethyl or propyl alcohol to water. Ammonia may be substituted for alcohol if the fumes are not objectionable. Alcohol or ammonia will reduce the oxide flash formed when the hot metal is transferred from the furnace to the quench tank.

The Nickel and MONEL nickel-copper alloys will have a silver-white surface after heating in a protective atmosphere and quick quenching in an alcohol-water solution. A gray tint on the Nickel alloys or a pink tint on the MONEL alloys indicates either oxygen in the furnace, delay in quenching, or too much alcohol in the solution.

The reducing quench will not produce a bright surface on the chromium-containing alloys, but it will minimize oxidation and aid subsequent pickling.

Heat treatments

When metals are plastically deformed at temperatures lower than their recrystallization points, they become work-hardened. That increases hardness and strength, decreases ductility, alters the grain structure, and develops stresses in the metal.

It is usually necessary to reduce or eliminate the stresses resulting from cold working and soften the metal by controlled heating before it can be further processed or placed in service. The principal heat treatments used to produce desired mechanical properties in the high-nickel alloys are stress equalizing, stress relieving, annealing, and precipitation hardening. The optimum temperature and time-at-temperature for any heat treatment depend on the composition, section size, and prior processing of the metal. Time and temperature are usually experimentally determined for each application. Guidelines for establishing heating times and temperatures are given in the bulletins which describe the alloys. Figure 17, for example, shows the changes in room-temperature properties that result from heating cold-drawn MONEL alloy 400 rod for 3 hours at various temperatures. The changes in properties with increasing temperature (and resultant reduction of stresses in the metal) are apparent.

Stress equalizing

Stress equalizing is a low-temperature heat treatment, usually requiring temperatures in the range of 500° to 700°F (260° to 370°C) for work-hardened nickel alloys. Stress equalizing is commonly described as partial recovery of cold-worked material. This recovery precedes any detectable microscopic structural changes and consists of a considerable increase in yield strength at 0.0% offset, a slight increase in hardness and tensile strength, and no significant change in elongation and reduction of area. In addition, stresses in the metal are balanced, and electrical conductivity returns toward the characteristic value of the material in the annealed condition.

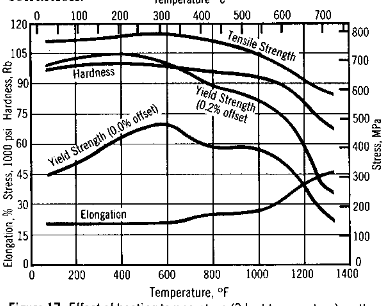

Figure 17. Effect of heating temperature (3 h at temperature) on the room temperature mechanical properties of a MONEL alloy 400 cold-drawn rod.

Figure 17 shows that stress equalization of a cold-drawn MONEL alloy 400 rod occurs in the temperature range of 450° to 600°F (230° to 315°C). Treatment for long periods of time in this temperature range has no detrimental effect.

Stress equalizing is a common treatment for coil springs, wire forms, and flat spring stampings. This treatment enables springs to withstand higher stresses and usually lengthens fatigue life. If coil springs are to be given a cold set or cold pressing after coiling, stress equalizing should be done before the setting operation. Cold setting involves stressing the material beyond the elastic limit, and the cold-working stresses set up in the spring are in such a direction that they are beneficial rather than harmful. Stress equalizing after cold pressing removes this beneficial cold work.

Stress relieving

Stress relieving reduces stresses in work-hardened, non-age-hardenable alloys without producing a recrystallized grain structure. This thermal treatment employs moderate temperatures, usually in the range of 900° to 1600°F (480° to 870°C), depending on composition and amount of work hardening. The purpose of the treatment is to remove more of the internal stresses than are removed by stress equalizing without appreciably decreasing the strength.

Stress relieving requires careful control of time and temperature. Continuous processes yield the best results for thin sections such as strip and tubing.

Those portions of the curves between 750° and 1100°F (400° and 595°C) in Figure 17 illustrate the effects of stress relief on the mechanical properties of MONEL alloy 400 cold-drawn rod. The reduction in stress causes slight decreases in yield strength, tensile strength, and hardness, and a slight increase in elongation.

Annealing

Work-hardened material can be softened completely by annealing. The treatment requires exposure to a sufficient temperature for a time long enough to cause full recrystallization of the work-hardened grain structure. That removes all of the stresses, softens the material, and decreases mechanical strength.

Temperatures in the range of 1300° to 2300°F (705° to 1260°C) are used to anneal the nickel alloys. Figure 17 shows that heating for 3 hours at 1300°F (705°C) or above produced an annealed condition in the specimen of cold-drawn MONEL alloy 400.

Recrystallization is a function of time, temperature, and amount of cold work as well as alloy composition. Table 9 shows the effect of these variables on INCONEL alloy 600 cold-rolled sheet.

Grain growth occurs when material is heated at higher temperatures or for longer times than those required for recrystallization. Although that results in further softening, a coarse grain structure is unsuitable for some cold-forming operations and many service conditions (for example, a fine grain is usually required for good fatigue strength).

A coarse grain cannot be refined in the high-nickel alloys by thermal treatment alone. It can be removed only by cold working to a degree that will result in recrystallization to a finer grain during subsequent annealing. If coarse grain is desired, or if maximum softness is required and coarse grain is not harmful to the application, the material can be given a solution anneal. Solution annealing, or solution treating, is performed by heating at temperatures in the upper part of the annealing range. The treatment is also used to dissolve the hardening elements in precipitation-hardenable alloys prior to aging.

Figure 18 illustrates the effects of annealing time and temperature on the grain size and room-

Table 9 —Effect of Cold Reduction on Recrystallization Temperature of INCONEL alloy 600[a]

Cold Reduction, %	Temperature Required for Recrystallization in Time Shown							
	15 min		30 min		60 min		120 min	
	°F	°C	°F	°C	°F	°C	°F	°C
5	1775	970	1750	955	1700	925	1700	925
10	1650	900	1600	870	1550	845	1550	845
20	1525	830	1475	800	1425	775	1425	775
50	1350	730	1325	720	1275	690	1275	690
80	1250	675	1225	665	1200	650	1200	650

[a]Cold-rolled, fine-grain sheet.

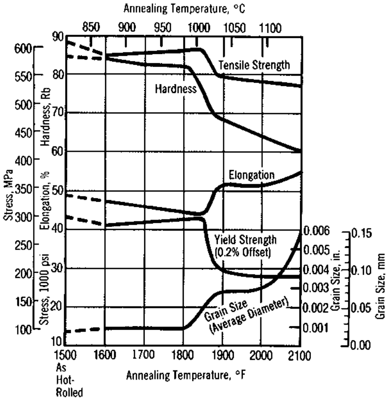

Figure 18. Effect of 15-min anneal on the grain size and room-temperature mechanical properties of an INCOLOY alloy 800 hot-rolled round 1 7/32 in. (31 mm) in diameter.

temperature mechanical properties of INCOLOY alloy 800 hot-rolled bar. Note that there is no increase in grain size until the temperature reaches about 1850°F (1010°C). A sharp increase in grain size occurs between 1850°F (1010°C) and 1900°F (1040°C). Above 1900°F (1040°C) the rate of grain growth slows. This behavior is typical of hot-rolled chromium-containing alloys such as INCONEL alloy 600, NIMONIC alloy 75, and INCOLOY alloy 800. At temperatures below about 1850°F (1010°C), these alloys contain finely dispersed chromium carbide particles which mechanically block grain growth. At 1850°F (1010°C), these carbides begin to coalesce and dissolve, and the rate of grain growth increases. At 1900°F (1040°C), solution is practically complete, and grain growth proceeds at a slower rate up to 2000°F (1095°C). Increasing the annealing temperature to above 2000°F (1095°C) causes a marked increase in the rate of grain growth.

Precipitation hardening

The precipitation-hardenable (age-hardenable) alloys are not softened by heating at intermediate temperatures (900° to 1600°F, 480° to 870°C). Instead, their hardness is increased by heating in this range. These alloys contain elements which form a metallurgical phase, usually gamma prime, upon exposure to appropriate temperatures. This phase is precipitated as sub-microscopic particles throughout the grains and causes a substantial increase in hardness and strength.

There are two systems of SMC age-hardenable (precipitation-hardenable) alloys. The first system, typified by MONEL alloy K-500, DURANICKEL alloy 301, NIMONIC alloy 80A, and INCONEL alloy X-750, utilizes aluminum and titanium to produce the gamma-prime precipitate. The second system, typified by INCONEL alloy 718, employs aluminum, titanium, and niobium.

The principal difference between the two systems is the rate at which precipitation occurs during heat treatment. Precipitation begins soon after exposure to temperature in the aluminum-titanium system, whereas a slight delay occurs in the aluminum-titanium-niobium system. The delay enhances weldability by preventing hardening during welding. The hardness developed by aging INCONEL alloy X-750 at various temperatures and times is shown in Figure 19.

These alloys are usually age-hardened in the solution-treated condition. However, they can be aged in the annealed or hot-worked or cold-worked condition. Solution treating is beneficial in some cases to develop maximum hardness or other special properties.

Precipitation hardening, like annealing, is time-temperature-dependent, and the optimum schedule for heat treatment varies with the alloy and the end use for the material. Specific procedures for heat treating the age-hardenable alloys are given in the appropriate technical bulletins, available from Special Metals Corporation.

MONEL alloy K-500, INCONEL alloy X-750, NIMONIC alloy 80A, and other age-hardenable alloys contain appreciable amounts of aluminum and titanium. Consequently, bright surfaces after age hardening are virtually impossible to achieve.

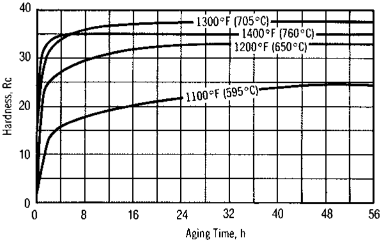

Figure 19. Effect of age hardening at various temperatures on hardness of hot-rolled INCONEL alloy X-750.

Hot Forming

Introduction

Nickel alloys, MONEL nickel-copper alloys, INCONEL nickel-chromium alloys, and INCOLOY nickel-iron-chromium alloys are readily hot-formed into almost any shape. Closed-die forgings include turbine blades, turbine discs, exhaust valves, chain hooks, heat-exchanger headers, valve bodies and pump bodies. Shafts and seamless rings are made by open-die forging. Seamless rings are also formed on ring rollers.

Most nickel alloys are stronger and stiffer than steel. Nickel 200 and MONEL alloy 400, however, are softer than many steels.

As an indication of their relative resistance to hot deformation, Table 10 shows the pressures developed in the roll gap at 20% hot-roll reduction for some nickel alloys and two steels at various hot-working temperatures. Higher pressures indicate greater resistance. Sufficiently powerful equipment is of particular importance when hot-forming INCOLOY alloy 800, INCONEL alloy 600, INCONEL alloy 625, NIMONIC alloy 75, and the precipitation-hardenable alloys (INCONEL alloy 718, INCONEL alloy X-750, and NIMONIC alloy 80A, for example); these alloys have been especially developed to resist deformation at elevated temperatures.

Table 10 - Hot-Forming Pressures

Alloy	Pressure in Roll Gap at 20% Reduction							
	psi x 10^3				MPa			
	1800 °F	1900 °F	2000 °F	2100 °F	980 °C	1040 °C	1095 °C	1150 °C
MONEL alloy 400	18.0	15.3	12.0	9.8	124	105	83	68
INCONEL alloy 600	40.8	34.6	28.3	22.3	281	239	195	154
INCONEL alloy 625	67.2	55.0	43.0	31.0	463	379	296	214
INCONEL alloy 718	63.3	55.8	48.3	41.0	436	385	333	283
INCONEL alloy X-750	48.6	43.3	38.4	33.3	335	299	265	230
Mild Steel	22.4	18.3	14.3	10.3	154	126	99	71
Type 302 Stainless Steel	27.8	24.3	21.4	18.0	192	168	148	124

Die materials and lubrication

Forging dies may be made of either straight carbon steel or alloy die steels. The choice of die material depends on the shape and size of the piece, the quantity to be produced and the alloy to be forged.

Carbon-steel dies are adequate for moderate production runs of small parts. For long production runs or for large or intricate shapes, alloy die steels are generally used.

The service life of alloy-steel dies used in drop-forging the high-nickel alloys usually ranges from 3000 to 10 000 pieces, depending on the size, shape, and tolerance to be maintained.

Forging dies may be lubricated to facilitate removal of the workpiece after forming. Sulfur-free lubricants are necessary; those made with colloidal graphite give good results.

Lubricants may be applied by either swabbing or spraying. Spraying is the preferred method as it produces more uniform coverage.

General instructions

General information on heating the SMC alloys is given in "HEATING," the preceding section of this bulletin. The time required to heat a given alloy to the hot-working temperature must be determined experimentally because of the wide variations in furnaces, furnace operation, and metal surface conditions.

Proper temperature during deformation is the most important factor in achieving hot malleability. Figure 20 shows the approximate temperature ranges for safely hot working various SMC alloys. Use of the lower part of the temperature range may be required for development of specific tensile properties.

Preheating all tools and dies to about 500°F (260°C) is recommended to avoid chilling the metal during working.

All portions of a part must receive some hot work after the final heating operation to achieve uniform mechanical properties.

Heavy forging should not be done so rapidly that the metal becomes overheated from working. Use of an optical pyrometer is recommended.

In hot-bending operations, the metal should be worked as soon as possible after removal from the furnace to avoid cooling before bending is completed.

In open-die forging, a series of moderate reduction passes along the entire length is preferred. In working a square section into a round, the piece should be worked down in the square form until it approaches the final size. It should then be converted to an oversized octagon before finishing into the round. Billet corners which will be in contact with dies should be chamfered rather than left square. The work should be lifted away from the dies occasionally to permit relief of local cold areas.

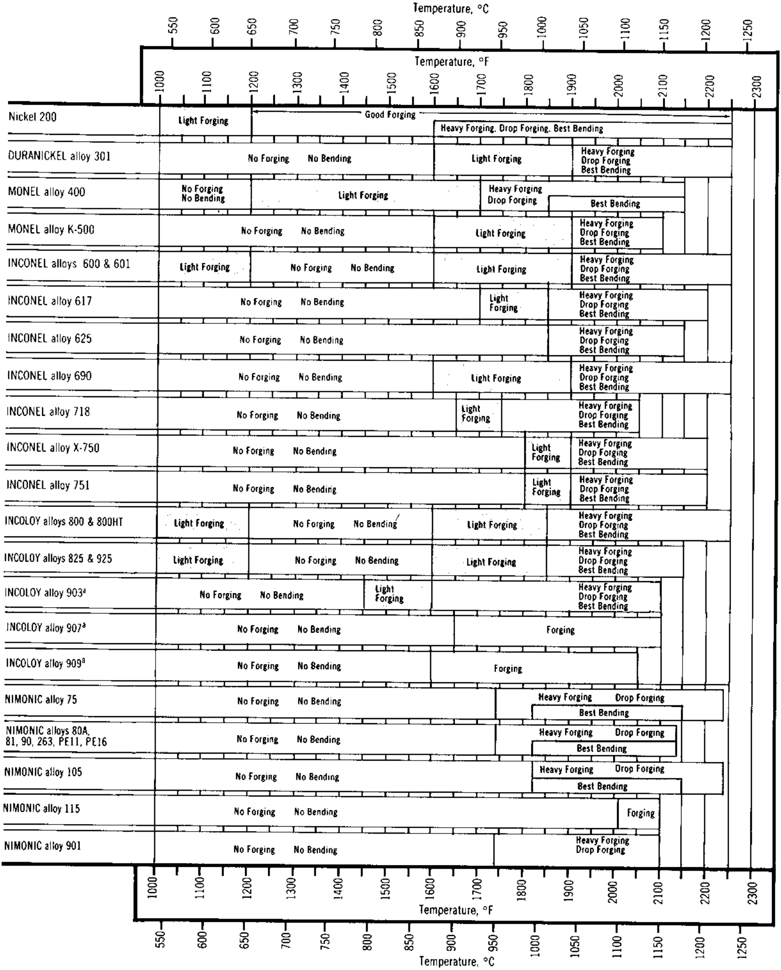

Figure 20. Temperature ranges for hot forming.

[a]See text for a note on the properties of the alloy.

The precipitation-hardenable alloys are subject to thermal cracking. For this reason, localized heating is not recommended. The entire part should be heated to the hot-working temperature.

If any ruptures appear on the surface of the material during hot working, they must be removed at once—either by hot grinding or by cooling the work and cold overhauling. If the ruptures are not removed, they may propagate into the body of the part.

Hot bending of tubular products

When possible, tube and pipe should be formed by cold bending as described in the cold-forming section of this bulletin. If hot bending is necessary, it is performed by standard hot-bending methods. Temperature ranges for hot bending are shown in Figure 20.

Hot bending is normally limited to tube and pipe larger than 2 in. Schedule 80, which has an outside diameter of 2.375 in. (60.52 mm) and a nominal wall thickness of 0.218 in. (5.54 mm). Thin-wall tubing should not be hot-bent since retaining sufficient heat to make the bend is difficult.

Bending should be done on filled tube only. Sand is the normal filler material. The sand must be free of sulfur since contamination by sulfur will cause cracking of the tube during bending (see Figure 21). Sulfur can be removed by heating the sand to about 2100° F (1150° C) in an oxidizing atmosphere.

Tubing must be cleaned thoroughly before filling or heating.

Sand-filled tube and pipe in small sizes—2 to 2½ in. (51 to 64 mm)—can be hot-bent to a minimum mean radius of two times the outside diameter of the tube. Larger sizes require greater bend radii.

Procedures

The following practices are used for general hot forming of the SMC alloys. Variations from these procedures may be necessary for some specialized applications. In such cases, specific recommendations should be obtained from **Special Metals Corporation.**

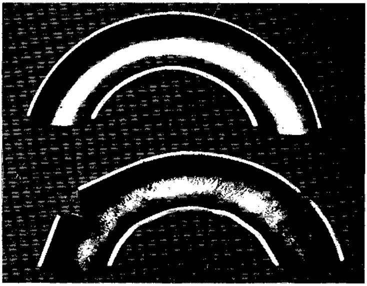

Figure 21. Hot-bent Nickel 200 tubing. The lower specimen was bent using sulfur-contaminated filler sand. The upper specimen was bent using sulfur-free filler sand.

Nickel 200

Nickel 200 should be charged into a hot furnace, withdrawn as soon as the desired temperature has been reached, and worked rapidly. The recommended range of hot-working temperatures is 1200° to 2250°F (650° to 1230°C). Because the metal stiffens rapidly when cooled to about 1600°F (870°C), all heavy work and hot bending should be done above that temperature. High mechanical properties can be produced by working lightly below 1200°F (650°C). The best range for hot bending is 1600° to 2250°F (870° to 1230°C).

The rate of cooling after hot forming is not critical, and Nickel 200 may be cooled by any method.

DURANICKEL alloy 301

The optimum temperature range for hot-working DURANICKEL alloy 301 is 1900° to 2250°F (1040° to 1230°C). Light finishing work can be done at a temperature of 1600°F (870°C). Finer grain size is produced in forgings by using 2150°F (1175°C) for the final reheat temperature and taking at least 30% reduction of area in the last forging operation.

After hot working, the alloy should be quenched from a temperature of 1450°F (790°C) or above. Quenching in water containing about 2% by volume of alcohol produces a less oxidized surface.

Material which must be cooled prior to subsequent hot working should also be quenched. Slow cooling may cause age hardening, which sets up stresses in the workpiece that can cause cracking during subsequent reheating.

MONEL alloy 400

The maximum heating temperature for hot-working MONEL alloy 400 is 2150°F (1175°C). Prolonged soaking at the working temperature is detrimental. If a delay occurs during processing, the furnace should be cut back to 1900°F (1040°C) and not brought to temperature until operations are resumed.

The recommended metal temperature for heavy reductions is 1700° to 2150°F (925° to 1175°C). Light reductions may be made at temperatures down to 1200°F (650°C). Working at the lower temperatures produces higher mechanical properties and smaller grain size.

A controlled forging procedure is necessary to meet the requirements of some specifications for forged, hot-finished parts. Both the amount of reduction and the finishing temperature must be controlled in order to develop the desired properties.

One procedure for producing forgings to such specifications consists of taking 30 to 35% reduction following the final reheat. This is accomplished as follows:

1. Reheat
2. Forge to a section having about 5% larger area than the final shape (take at least 25% reduction.
3. Cool to 1300°F (705°C).
4. Finish to size (5% reduction).

High-tensile forgings, as described in certain military specifications, also require a minimum of 30 to 35% reduction following the last reheat. This is taken in the following manner:

1. Reheat
2. Forge to a section having an area about 25% larger than the final shape (take about 5% reduction).
3. Cool to 1300°F (705°C).
4. Finish to size (25% reduction).

Grain refinement is achieved by using a temperature of 2000°F (1090°C) for the final reheat and by increasing the amount of reduction taken after the last reheat.

The rate of cooling after hot working is not critical, and MONEL alloy 400 may be cooled by any method.

MONEL alloy K-500

Maximum recommended heating temperature for hot-working MONEL alloy K-500 is 2100°F (1150°C). Metal should be charged into a hot furnace and withdrawn when uniformly heated. Prolonged soaking at this temperature is harmful. If a delay occurs, such that the material would be subject to prolonged soaking, the temperature should be reduced to or held at 1900°F (1040°C) until shortly before ready to work, then brought to 2100°F (1150°C). When the piece is uniformly heated, it should be withdrawn. In the event of long delay, work should be removed from the furnace and water quenched.

The hot-working temperature range is 1600° to 2100°F (870° to 1150°C). Heavy work is best done between 1900° and 2100°F (1040° to 1150°C), and working below 1600°F (870°C) is not recommended. To produce finer grain in forgings, the final reheat temperature should be 2000°F (1090°C) and at least 30% reduction of area should be taken in the last forging operation.

When hot working has been completed, or when it is necessary to allow MONEL alloy K-500 to cool before further hot working, it should not be allowed to cool in air but should be quenched from a temperature of 1450°F (790°C) or higher. If the part is allowed to cool slowly it will self-heat-treat (age-harden) to some extent, and stress will be set up that may lead to thermal splitting or tearing during subsequent reheating. In addition, quenched material has better response to age hardening, since more of the age-hardening constituent is retained in solution.

INCONEL alloys 600 and 601

The normal hot-working temperature range for INCONEL alloys 600 and 601 is 1600° to 2250°F (870° to 1230°C). Heavy hot work should be done in the 1900° to 2250°F (1040° to 1230°C) temperature range, and light working can be continued down to 1600°F (870°C). Generally, the alloy should not be worked between 1200° and 1600°F (650° to 870°C) because of its low ductility in that temperature range. Light working below 1200°F (650°C) will develop higher tensile properties.

The rate of cooling following hot working is not critical with respect to thermal cracking. INCONEL alloys 600 and 601 should, however, be rapidly cooled through the temperature range of 1000° to 1400°F (540° to 760°C) if subsequent use dictates freedom from sensitization.

INCONEL alloy 617

The hot-forming characteristics of INCONEL alloy 617 are similar to those of INCONEL alloy 625. Alloy 617 has good hot formability, but it requires relatively high forces because of its inherent high strength at elevated temperatures. The temperature range for heavy forming and forging is 1850° to 2200°F (1010° to 1205°C). Light working can be carried out at temperatures down to 1700°F (925°C).

Like INCONEL alloy 600, INCONEL alloy 617 is subject to carbide precipitation during cooling from hot-forming temperatures. Where such precipitation is to be avoided, the part should be water quenched or rapidly air cooled.

INCONEL alloy 625

INCONEL alloy 625 should be heated in a furnace held at 2150°F (1175°C) but no higher. The work should be brought as close to 2150°F (1175°C) as conditions permit. Hot forming is carried out from this temperature down to 1850°F (1010°C). Below 1850°F (1010°C) the metal is stiff and hard to move, and attempts to forge it may cause hammer splits at the colder areas. The work should be returned to the furnace and reheated to 2150°F (1175°C) whenever its temperture drops below 1850°F (1010°C). To guard against duplex grain structure, the work should be given uniform reductions. Final reductions of a minimum of 20% for open-die work are recommended.

While the rate of air cooling is generally not critical for INCONEL alloy 625, very slow cooling should be avoided. Furnace cooling of INCONEL alloy 625 is not recommended.

INCONEL alloy 690

The temperature range for heavy hot-forming of INCONEL alloy 690 is 1900° to 2250°F (1040° to 1230°C). Light forming can be performed at temperatures down to 1600°F (870°C). The rate of subsequent cooling is not critical, and INCONEL alloy 690 may be cooled by any method.

INCONEL alloy 718

INCONEL alloy 718 is strong and offers considerable resistance to deformation during hot working. The forces required for hot deformation are somewhat higher than those employed for INCONEL alloy X-750.

Hot working is performed in the 1650° to 2050°F (900° to 1120°C) temperature range. In the last operation, the metal should be worked uniformly with a gradually decreasing temperature, finishing with some light reduction below 1750°F (955°C).

In heating for hot working, the material should be brought to the proper temperature, allowed to soak a short time to ensure uniformity, and withdrawn.

To avoid the formation of duplex grain structure, INCONEL alloy 718 should be given uniform reductions. Final reductions of 20% minimum should be used for open-die work, and 10% minimum for closed-die work. Parts should generally be air-cooled from the hot-working temperature rather than water-quenched.

INCONEL alloy X-750

The hot-working range for INCONEL alloy X-750 is 1800° to 2200°F (980° to 1205°C). Below 1800°F (980°C) the metal is stiff and hard to move, and attempts to work it may cause splitting. All heavy hot working should be done at temperatures above 1900°F (1040°C) and the metal reheated whenever it cools below that temperature. Forgings can be finished with some light reduction in the 1800° to 1900°F (980° to 1040°C) range.

As a general rule, INCONEL alloy X-750 should be air-cooled rather than liquid-quenched from the hot-working temperature. Liquid quenching can cause high internal stresses that may result in cracking upon subsequent heating for further hot work or for heat treatment. Parts with large cross sections and pieces with variable cross section are especially prone to thermal cracking on cooling. For parts with very large cross sections, furnace cooling may be necessary to prevent thermal cracking.

INCONEL alloy 751

INCONEL alloy 751 is hot worked using procedures and temperatures the same as those used for INCONEL alloy X-750.

INCOLOY alloys 800 and 800HT

Hot working of INCOLOY alloys 800 and 800HT is started at 2200°F (1205°C), and heavy forging is done at temperatures down to 1850°F (1010°C). Light working can be accomplished down to 1600°F (870°C). No working should be done between 1600° and 1200°F (870° to 650°C). As with INCONEL alloy 600, thermal cracking is not a problem, and material should be water-quenched or air-cooled rapidly through the 1000° to 1400°F (540° to 750°C) range to ensure freedom from sensitization.

INCOLOY alloy 825

The hot-working range for INCOLOY alloy 825 is 1600° to 2150°F (870° to 1175°C). It is imperative that some reduction be accomplished in the 1600° to 1800°F (870° to 980°C) temperature range during final hot working to ensure maximum corrosion resistance.

Cooling after hot working should be done at a rate equal to or faster than air cooling. Heavy sections may become sensitized during cooling from the hot-working temperature and therefore subject to intergranular corrosion in certain media.

INCOLOY alloy 903

INCOLOY alloy 903 should be hot-worked in the 1500° to 2050°F (815° to 1120°C) temperature range. For applications in which high stress-rupture properties are required, the alloy should be given a minimum of 40% reduction at temperatures of 1500° to 1600°F (815° to 870°C). When tensile properties govern, alloy 903 may also be worked at the hotter end of the recommended range. Since INCOLOY alloy 903 is softer than INCONEL alloy X-750 between 1600° and 2000°F (870° and 1095°C), forming forces are lower than those for alloy X-750. INCOLOY alloy 903 should be rapidly air cooled after hot working.

INCOLOY alloy 907

INCOLOY alloy 907 has hot-working characteristics similar to those of INCONEL alloy 718. The temperature range for hot working is 1650° to 2100°F (900° to 1150°C). Some hot working should be done at 1850° to 1950°F (1010° to 1065°C) to refine the grain structure. A final reduction of at least 20% at a temperature under 1800°F (980°C) is needed for optimum mechanical properties.

INCOLOY alloy 909

The temperature range for hot forming of INCOLOY alloy 909 is 1600° to 2050°F (870° to 1120°C). The following sequence is recommended to achieve an optimum combination of tensile and rupture properties.

1. Initial forging after the metal has been heated to 1940° to 2050°F (1060° to 1120°C).
2. Intermediate forging with 25% reduction after a heating temperature of 1825° to 1925°F (995° to 1050°C). A warm-work and reheat sequence at this stage will produce grain refinement, a lower recrystallization temperature, and improved properties in the finished product.
3. Finish forging with 20% to 25% reduction after a heating temperature of 1800° to 1875°F (980° to 1025°C). The temperature of the workpiece should be lower than 1750°F (955°C) during most of the finishing operation.

Hot-formed material should not be cooled by water quenching. Air cooling is recommended. High stresses developed in the metal by water quenching may lead to unfavorable precipitate morphology and resultant lower tensile properties.

INCOLOY alloy 925

INCOLOY alloy 925 has hot-working characteristics similar to those of INCOLOY alloy 825 at temperatures up to 2000°F (1095°C). At higher temperatures, INCOLOY alloy 925 has lower ductility and higher strength. The hot-working range for INCOLOY alloy 925 is 1600° to 2150°F (870° to 1175°C). For maximum corrosion resistance and highest mechanical properties after direct aging, final hot working should be done in the 1600° to 1800°F (870° to 980°C) range.

NIMONIC alloys

Hot forming of precipitation-hardenable nickel alloys, a group that includes most of the NIMONIC alloys, requires stringent controls for good results. Those alloys are more sensitive than other nickel alloys to process parameters such as working temperatures, amount of reduction, lubrication, and rate of heating or cooling.

The most widespread use of hot forming for NIMONIC alloys is the forging of gas-turbine components, particularly discs and blades. Although those two components are normally of different magnitude in size, they are forged by similar practices. The following information describes typical procedures for production of turbine blades in NIMONIC alloys.

Turbine blades are produced by various forging processes that fall generally into two categtories: (1) Oversize forging to a +0.04 to +0.08 in. (+1 to +2 mm) envelope on the airfoil and (2) precision forging to a +0.004 to +0.01 in. (+0.1 to 0.25 mm) envelope on the airfoil. Finishing of precision-forged blades consists only of machining the root and shroud blocks and polishing the airfoil.

The first operation is the cutting of the starting stock into lengths having the required weight. Cutting is best done with an abrasive wheel under close control. For NIMONIC alloys 105 and 115, the cutting wheel must be liquid cooled, and the machine must be of interrupted-cut type. Otherwise, high thermal stresses may develop at the cut surfaces and cause cracking when the material is reheated for forging.

The cut pieces can be readied for forging by partial extrusion, "necking down" with quick-acting hammers, interrupted rolling, or upsetting. The object is to redistribute the volume of material, mainly to the root and shroud areas, to permit final forging within controlled parameters. Proper shaping at this point ensures uniformity of properties in the finished blade, minimizes metal loss from flash, and reduces die wear.

The final component can be forged with a variety of equipment, but a large-capacity crank or screw press is recommended. Such a press often makes possible completion of forging with only two additional reheatings. The first operation is done with a preforming die that produces a form that, after flash removal, is of the correct volume to permit finishing with one further blow. The finished blade normally has a grain-size specification that requires close control of temperature and overall reduction during the final blow. In precision forging, an intermediate blow is usually necessary to achieve the close volumetric limits needed in the final die.

The use of drop hammers is not recommended, particularly for the final blow. Drop hammers do not provide consistent control of dimensions and grain size in the forged component. Also, a reheat for each blow as well as the final trimming operation is recommended.

Forging temperatures for turbine blades are more restrictive than temperatures for general forging. NIMONIC alloys 80A and 90 should be forged at 2070° to 2155°F (1130° to 1180°C). NIMONIC alloy 105 should be forged at 2085° to 2120°F (1140° to 1160°C). For NIMONIC alloy 115, the temperature range is 2030° to 2085°F (1110° to 1140°C). Trimming of flash should not be done immediately after forging. The workpiece should be reheated to a proper temperature. Flash can be trimmed from NIMONIC alloys 80A and 90 in the range of 1560° to 1830°F (850° to 1000°C). For trimming of NIMONIC alloy 105 and 115, the temperature should be closely controlled at 1830°F (1000°C). Flash-trimming tools must be maintained in excellent condition to avoid small tears or cracks on the edge of the forged blade that could propagate into the body of the blade during subsequent forging.

Forging dies are usually high-tungsten steel or Ni-Cr-Mo-V steel. Die life varies considerably depending on the design of the component and die and on the tolerances needed for the finished part. A life of 300 to 400 turbine blades may be obtained in precision forging or over 1000 blades of the outsize type.

Lubrication of the dies is necessary to prevent sticking and to aid metal flow. For the less-complex alloys, a solution of graphite in a carrier (water, white spirit, or lanolin) can be brushed or sprayed on the dies. The highly complex alloys require, in addition to graphite lubrication of the dies, coatings of nickel or glass applied by plating methods to a thickness of about 0.04 in. (1 mm). Glass may be applied by either dipping the component in a colloidal suspension of glass or electrostatic spraying of the glass suspension.

Components should be allowed to cool freely in air after each forging operation, especially the last. Cooling on raised and perforated racks that allow air to circulate is preferred. Quenching in water or oil is not recommended.

Introduction

Oxide, scale, tarnish, or discoloration can be removed from nickel alloys by mechanical methods such as grinding or abrasive blasting or by a chemical method such as pickling. Abrasive blasting is sometimes the most suitable method because it requires low capital investment and eliminates the use and disposal of acids. Pickling, however, is a standard method for producing bright, clean surfaces on the SMC alloys, either as an intermediate step during fabrication or as a last step on finished parts.

Procedures used for pickling the alloys are governed by both composition and prior thermal treatment of the material. It is always best to avoid the necessity of pickling by using bright-heating practices. Pickling should not be used to overhaul material by dissolving away appreciable amounts of metal. This practice can cause severe damage.

Oxidizing furnace atmospheres, high-sulfur-content fuels, and air leakage in furnaces cause heavy scale to form on nickel alloys. The metal has a dull, spongy appearance, sometimes with hairline cracks, and patches of scale may break away from the surface. In such cases, the underlying metal is rough and an attractive finish cannot be attained by any pickling method.

Abrasive blasting or grinding, followed by flash pickling, is usually the best method for removing heavy scale. An alternative method is to soak the work in the hydrochloric acid pickle (discussed later as Formula K), followed, if brightening is necessary, by flash pickling.

All formulas referred to in this section are listed with their compositions on the inside back cover of this bulletin. For ease of formulation, the acids and their specific gravities are given below.

Acid	°Baumé	Specific Gravity	Concentration, % by wt.
HNO_3	42	1.41	67
H_2SO_4	66	1.84	93
HCl	20	1.16	32
HF	30	1.26	70

Precautions

The usual precautions must be taken in handling pickling solutions. Noxious and sometimes toxic fumes are liberated during pickling. Positive ventilation, either by using a ventilating hood over the bath or by providing a controlled draft, is required to remove the fumes. Acids must be handled with care, particularly hydrofluoric acid. Protective clothing, face shields, and rubber gloves must be used. In making up solutions, the acid must always be added to the water. This is especially important when diluting sulfuric acid. In making the solutions shown in this bulletin, the other ingredients should be added to water in the order listed.

Bath life

Pickling baths should be analyzed periodically and their acidity determined. In baths composed of more than one acid, only the total acidity is determined; it is impossible to distinguish acidity contributed by one acid source from that contributed by another. However, in maintaining a bath, ingredients should be added in the proportions used for the original solution. Sufficient additions should be made to restore the bath to the initial acidity level.

With the exception of flash-pickling solutions, baths should be disposed of and fresh ones prepared when the total metallic content reaches 150 g/L. If the bath is used for only one type of alloy, only one element need be determined in the analysis. Other metallic elements can be determined from the percentage of each in the composition of the alloy. For example, in analyzing baths used for pickling INCONEL nickel-chromium alloys, only the nickel content is necessary to determine whether the total metallic content is within the 150 g/L limitation.

Flash-pickling solutions work well even when nearly saturated with metal salts. Fresh solutions should be made up when salts begin to crystallize out on the sides of the container.

Alloy groups

For the purpose of discussing pickling procedures, the SMC alloys can be divided into three groups:

1. Nickel alloys. Included in this group are Nickel 200, Nickel 201, Nickel 270, DURANICKEL alloy 301, and similar alloys composed primarily of nickel.
2. Nickel-copper alloys. Included are MONEL alloys 400, K-500, and others.
3. Nickel-chromium and nickel-iron-chromium alloys. Examples of nickel-chromium alloys are INCONEL alloys 600, 625, 718, and X-750, and NIMONIC alloys 75, 80A, and 105. INCOLOY alloys such as alloys 800 and 825 make up the nickel-iron-chromium group.

All of the alloys within any one group have virtually the same pickling characteristics. However, the pickling procedures for the alloys within a group must be varied to suit the surface condition of the metal.

Surface conditions

With equivalent surface conditions, the alloys within each compositional group are pickled in the same solutions and by the same procedures. Three different surface conditions, primarily depending on the method of prior heating, are generally encountered:

1. Bright-annealed white metal requiring removal of tarnish by flash pickling.
2. Bright-annealed oxidized metal requiring removal of a layer of reduced oxide, sometimes followed by a flash pickle to brighten.
3. Black or dark-colored surface requiring removal of adherent oxide film or scale.

Tarnish

Flash pickling, or bright dipping, is used to remove tarnish and dullness from bright-annealed metal. Bright-annealed white surfaces are generally found on drawn and spun shapes, cold-headed rivets, cold-drawn wire, and other cold-worked products. The white surface results after annealing in a reducing, sulfur-free atmosphere, and cooling either out of contact with oxygen or by quenching in a 2% (by volume) alcohol solution.

Flash-pickling solutions act rapidly and care must be exercised to prevent over-pickling and etching. The solutions are used at room temperature; if the bath is cold, it should be warmed slightly to prevent unduly slow action.

Best results are obtained in flash pickling by first warming the parts by a dip in hot water, then placing them in the acid for a few seconds, and rinsing with hot water. A second dip in the acid should be used if necessary. Badly tarnished metal may require a total of 3 minutes in the acid, but, to prevent over-pickling, the material should be frequently withdrawn from the bath and inspected.

Reduced oxide

Reduced oxide occurs on hot-worked products such as forgings and hot-rolled material that have been heated after hot working in a reducing, sulfur-free atmosphere and cooled out of contact with air or quenched in an alcohol solution. Such hot-worked products are pickled to produce a clean surface for further processing by cold forming, or to produce the finished surface on items such as rivets.

At annealing temperatures in reducing atmospheres, the oxides formed on the high-nickel alloys, except those containing chromium, are readily converted to a spongy, tightly adherent layer. On Nickel alloys, the layer consists of metallic nickel; on MONEL alloys it is a mixture of metallic nickel and copper.

The oxide film formed on nickel-chromium (INCONEL and NIMONIC alloys) and nickel-iron-chromium (INCOLOY alloys) does not undergo complete reduction and makes pickling more difficult. The oxide on these alloys is selectively reduced to a mixture of metallic nickel and chromic oxide. The color of the surface ranges from the characteristic chrome green of chromic oxide to dark brown.

Oxide or scale

All hot-worked products and heat-treated material cooled in air have oxidized or scaled surfaces. This type of surface also occurs on the nickel-chromium and nickel-iron-chromium alloys in all conditions except bright-heated.

The oxide film on nickel and nickel-copper alloys that have been heated properly is formed during contact with air after the work is withdrawn from the furnace. The nickel-chromium and nickel-iron-chromium alloys form oxide films even when heated and cooled in atmospheres that keep other alloys bright. Thus, the usual pickling procedure for INCONEL, NIMONIC, and INCOLOY alloys is one designed to remove oxide and scale.

Nickel-copper alloys

Depending on the method of prior heating and cooling, MONEL nickel-copper alloys can have any of the previously discussed surface conditions. Accordingly, the appropriate pickling procedure depends on the surface condition of the material.

Tarnished surface

Tarnish is best removed from bright-annealed nickel-copper alloys by pickling in two solutions in sequence. First, the metal should be pickled thoroughly in Formula B, in brief exposures, and rinsed in water at 180°F (80°C). Second, after rinsing, the metal should be dipped in Formula A. The second dip is to be followed by rapid rinsing and neutralization in a 1 to 2% solution (by volume) of ammonia (Formula N). Small workpieces can be dried by being dipped in boiling water and rubbed in sawdust or with a clean, dry cloth.

Reduced-oxide surface

Formula H is recommended for reduced-oxide surfaces on nickel-copper alloys if pickling is done on a large-scale basis in fully equipped plants. This acid mixture is more destructive to tanks and racks than solutions used for steel or copper. Steel tanks lined with 3/16-in. (4.8-mm) thick natural rubber and a double layer of yellow acid bricks have proven to be the best and most economical containers for this corrosive solution.

After pickling in Formula H, the metal should be rinsed in hot water and neutralized in a 1 to 2% (by volume) ammonia solution.

The pickling solution (Formula H) works better after a short period of use than when initially prepared. Therefore, in making up new solutions, about 2% (by volume) of spent solution should be added to the fresh mixture to improve its action.

The time required for complete pickling of small lots in Formula H is usually a disadvantage when a pickling room is not regularly operated, and adequate results in most cases can be obtained by using flash-pickling solutions (Formulas B and A). However, Formula H may be used for occasional small jobs, utilizing ceramic vessels or wooden barrels as containers. The solution can be heated and agitated by injecting live steam either through a rubber hose or a carbon pipe having a perforated carbon-block end.

Oxidized or scaled surface

Oxidized nickel-copper alloys having a thin to moderately thick oxide are pickled by immersion in Formula K followed by brightening in Formula F. After treatment in the first bath, the work should be rinsed in hot water before being transferred to the brightening dip. The second dip (Formula F) should be followed by rinsing in cold water and neutralizing in a 1 to 2% (by volume) ammonia solution (Formula N).

Nickel alloys

Nickel 200, Nickel 201, Nickel 270, DURANICKEL alloy 301, and similar alloys can have any of the three types of surface conditions. With the exception of flash pickling, the Nickel alloys are pickled in the same solutions used for MONEL alloys. However, it is usually advisable to maintain separate baths for the two groups of alloys.

Tarnished surface

Only one dip, Formula I, is required to remove tarnish from bright-annealed Nickel alloys. The metal should be warmed first by dipping in hot water. Immersion in the acid bath for 5 to 20 seconds is usually sufficient to produce bright, clean surfaces. After removal from the pickling solution, the metal should be rinsed in hot or cold water and neutralized in a dilute ammonia solution.

The pickling action of Formula I can be retarded, if necessary, by decreasing the amount of acid to as little as one-third the volume that is added to the standard formula—that is, as low as 400 mL of sulfuric acid and 620 mL of nitric acid. Normally, however, the formula gives the best results as it is written.

Reduced-oxide surface

The solution used to pickle reduced-oxide surfaces on nickel-copper alloys, Formula H, is also used for the Nickel alloys. The procedure described for reduced-oxide surfaces under "NICKEL-COPPER ALLOYS" should be followed. If both groups of alloys are being pickled, separate baths should be maintained.

Formula H may be used for occasional small lots, but suitable results can usually be obtained in less time by flash pickling in Formula I.

Oxidized or scaled surface

The hydrochloric acid/cupric chloride solution (Formula K) used for nickel-copper alloys is also used to pickle oxidized or scaled surfaces on Nickel alloys. However, a longer time is required. From 1 to 2 hours' immersion is necessary to obtain a good pickle on the Nickel alloys.

After removal from the pickling bath, the work should be rinsed with hot water and, if brightening is required, dipped for a few seconds in Formula I. The brightening dip should be followed by a cold-water rinse and neutralization in a dilute ammonia solution.

Nickel-chromium and nickel-iron-chromium alloys

Tarnished or reduced-oxide surfaces are usually not encountered on INCONEL and NIMONIC nickel-chromium or INCOLOY nickel-iron-chromium alloys. These alloys can be bright-annealed only in very dry hydrogen or in a vacuum, and oxides formed on their surfaces in other atmospheres do not undergo complete reduction. Oxide or scale is therefore the usual surface to be pickled on nickel-chromium and nickel-iron-chromium alloys.

Pretreatment in a fused-salt bath is strongly recommended to facilitate pickling of oxidized or scaled surfaces. However, if the metal has been properly heated and cooled, it will usually have a surface suitable for direct pickling in Formula C.

If a fused-salt bath is available for pretreatment, the following procedure gives good results in pickling nickel-chromium and nickel-iron-chromium alloys:

1. Treat in fused-salt bath.
2. Quench in and spray with water.
3. Immerse in Formula D.
4. Withdraw from bath and rinse with water.
5. Immerse in Formula A.
6. Withdraw from bath and rinse with water.
7. Pickle in Formula C as required.

As with the nickel-copper MONEL alloys and Nickel alloys, an alternative procedure employing a salt bath and Formula H (with the addition of 10 g of ferric chloride per litre to the formula) effectively removes oxide from hot-rolled or annealed INCONEL alloy 601 and INCOLOY alloy 903. See the procedure for the use of a salt bath described under Oxidized or Scaled Surfaces under "NICKEL-COPPER ALLOYS."

If the oxide film cannot be readily removed by direct pickling in Formula C, and if a fused-salt bath is not available, Formula M is useful as a pretreatment. After soaking for 1 to 2 h in Formula M, the work is removed, rinsed to remove all of the caustic solution, and pickled in Formula C. On particularly refractory oxides, it is sometimes necessary to repeat the cycle.

The addition of 7 to 10 grams of iron per litre to Formula C decreases the danger of over-pickling. That can be conveniently done by adding the proper weight of scrap iron to the bath when it is made up.

The nitric acid/hydrofluoric acid bath (Formula C) must be used with care. Nickel-chromium and nickel-iron-chromium alloys are subject to intergranular attack in this solution if they have been sensitized by heating in or slowly cooling through the 1000° to 1400°F (540° to 760°C) temperature range. Time in the bath should be kept to a minimum, and bath temperature must not exceed 125°F (50°C). Stress-relieved and age-hardened material can be sensitive to intergranular attack if the heat treatment involved exposure to sensitizing temperatures.

Salt baths

Pretreatment baths of fused salts aid in the pickling of many alloys. They are particularly effective in pickling nickel-chromium and nickel-iron-chromium alloys and are strongly recommended for the SMC alloys of those compositions. Several proprietary baths are commercially available; information on their use can be obtained from the manufacturers.

Salt baths are of three types: reducing, oxidizing, and electrolytic. Oxidizing baths are usually the least expensive to operate and the easiest to control. Reducing baths, however, are not in common use today. Electrolytic baths, although more expensive to install and operate, are quite effective.

Oxidizing baths

Oxidizing salt baths have a base of either sodium hydroxide or potassium hydroxide. Other salts such as sodium nitrate and sodium chloride are added to provide controlled oxidizing properties.

The sodium hydroxide bath is operated at temperatures of 800° to 1000°F (425° to 540°C); 900°F (480°C) is preferred for descaling Huntington alloys. The potassium hydroxide bath operates at lower temperatures, usually 400° to 500°F (205° to 260°C).

Treatment time in oxidizing baths is usually 5 to 20 min. However, in the operation of continuous strand-pickling lines, the time may be as short as 15 to 60 seconds.

The salt bath oxidizes the lower oxides on the surface of the work to form soluble salts and water. Quenching after treatment removes part of the scale and loosens the remainder so that it is easily removed by appropriate acid dips.

Oxidizing salt baths are also effective cleaners. They remove oils, greases, organic materials, and some inorganic substances from metal surfaces.

Electrolytic baths

Although the electrolytic salt bath can be used as a batch process, it is more suitable for continuous operations such as descaling of strip.

The bath has a sodium hydroxide base and contains other salts such as sodium chloride and sodium carbonate which, when electrically activated, form reducing agents at the cathode and oxidizing agents at the anode. The bath is usually operated at about 900°F (480°C).

Two tanks are normally used for continuous processes. The work is made anodic in the first tank and cathodic in the second.

Specialized pickling operations

Although pickling is most often used to remove the oxide or scale formed during heating, it is also a convenient means of removing foreign metals and other substances. Several procedures specifically designed for such purposes are applicable to the Inco alloys.

Removal of lead and zinc

Lead and zinc will embrittle the high-nickel alloys at elevated temperatures. Consequently, when the alloys are formed in dies made of materials which contain lead and zinc, it is important to remove all traces of the die material picked up during forming. This is especially important when the parts will be given intermediate anneals for processing or will be exposed to high temperatures during service.

Formula J is used to remove lead and zinc from nickel and nickel-copper alloys. For the nickel-chromium and nickel-iron-chromium alloys a bath of nitric acid similar to Formula A (but at a higher concentration of 30%) is used. After immersion for 15 min in the appropriate bath, the work is removed, rinsed in water, and dried.

Detection and removal of embedded iron

During rolling to shape, hot pressing, or other mechanical operations, small particles of iron may become so firmly embedded in the surfaces of nickel alloys that they cannot be removed by the cleaning methods normally used for dissolving grease or cutting compounds. Under certain corrosive conditions, such iron particles can initiate local attack. For that reason it is often necessary to test for and to remove any iron.

For large-scale testing, a solution consisting of about 1% sodium chloride gives good results. The salt should be of the chemically pure grade to avoid false results from iron that might be present in less pure grades. After 12 to 24 h in the dilute salt solution, iron particles can easily be detected by examining for rust deposits. It is usually less expensive, when compressed air is available, to keep the tank full of salt spray with an atomizer than to fill it with the solution.

The ferroxyl test works well for small-scale testing. The test is carried out by applying a potassium ferricyanide solution to the surface of the material. The solution should be made up in approximately the proportions shown in Formula P.

The ingredients are mixed in earthenware, glass, or ceramic vessels and then boiled until all of the agar-agar is dissolved and a clear liquor is formed. Chemically pure sodium chloride should be used to avoid iron contamination of the test solution.

The warm solution is applied to the surface to be tested and allowed to remain for at least 1 h.

The solution jells as it cools, and the presence of iron on the metal surface is indicated by blue spots in the jell.

The ferroxyl test is so sensitive that minute particles of iron that collect on the surface in the form of shop dust will appear as small blue spots in the jell. Since the iron dust will be washed off with the jell, a distinction should be made between the small spots and the larger ones caused by embedded iron. When spots of relatively major proportions develop, large iron particles are probably present.

A solution of hydrochloric acid and ferric chloride, Formula L, is used to remove the embedded iron. This solution should be used cold and should remain in contact with the metal for only the minimum time required for iron removal. Treatment time should not be more than 1 h. After removal from the solution, the work should be thoroughly rinsed in cold water, rinsed again in warm water, and the detection tests repeated to verify removal of the iron.

Prevention and removal of copper flash

Copper flash sometimes forms on the surface of nickel alloys during pickling. For copper deposits to form, the copper ions in the solution must be in the cuprous state or must pass from the cupric to the cuprous state during the cementing process. Consequently, any agents in the pickling bath that tend to maintain the cupric state will help prevent coppering.

Oxidizing agents such as nitric acid and sodium nitrate promote the action of pickling solutions but become depleted with use. As the pickling bath ages, the concentration of copper ions increases and that of the oxidizing agents decreases. Thus, aging of the bath is conducive to coppering on areas where the reducing effect of the metal exceeds the oxidizing power of the bath.

When coppering occurs on MONEL alloy 400 and other high-nickel alloys that contain an appreciable amount of copper, the bath can be restored by the addition of small amounts of nitric acid or sodium nitrate. Nickel has greater reducing capacity than MONEL alloy 400 and consequently requires a greater concentration of oxidizing agents to prevent coppering in solutions containing copper salts. For this reason, Nickel 200 and similar alloys cannot be pickled in solutions that have been used for nickel-copper alloys without adding a considerable quantity of nitric acid or sodium nitrate to the bath.

Patches of copper will plate out on nickel-copper alloys if steel contacts the alloys while they are wet with acid. Steel tongs or other devices used to handle the work are the usual sources of coppered areas. Coppering is prevented by using tongs, wires, or other handling devices made of Nickel 200 or MONEL alloy 400.

Copper flash is readily removed by immersing in an aerated, 4 to 5% ammonia solution (approximately 1 pt of commercial aqua ammonia to 1 gal of water or 125 mL of ammonia to 1 litre of water) at room temperature. The time required is short, usually about 1 min. The work should be rinsed in water after dipping in the ammonia solution.

Electrolytic pickling

Light oxide films on any of the Inco alloys can be removed by electrolytic pickling in Formula G. The work should be made anodic. A current density of 50 to 100 A/ft^2 (540 to 1075 A/m^2) is used.

Electrolytic pickling is also useful for etching ground material to obtain a surface suitable for inspection.

Cleaning of springs

In general, cleaning after heat treatment is not recommended for springs of the high-nickel alloys. The oxide on heat-treated springs is usually beneficial in resisting corrosion at high temperatures, and resistance to relaxation is often lowered when the oxide is removed.

If cleaning is necessary for inspection of the springs, treatment in a salt bath followed by water quenching and rinsing produces a good surface. Table 11 shows the effect of the cleaning method on resistance to relaxation of INCONEL alloy X-750 springs age hardened at 1350°F (730°C)/16 h.

Cleaning for welding

Before maintenance welding is done on high-nickel alloys that have been in service, products of corrosion and other foreign materials must be removed from the vicinity of the weld. Clean, bright base metal should extend 2 to 3 in. (50 to 75 mm) from the joint on both sides of the material. This prevents embrittlement by corrosion products at welding temperatures. Cleaning can be done mechanically by grinding with a fine wheel or disc, or chemically by pickling.

Flash-pickling solutions are effective in cleaning before welding. The solutions may be applied by swabbing or brushing, or, if the parts are easily handled, by dipping. One dip in Formula B is adequate for the MONEL nickel-copper alloys. Formula A is used for Nickel alloys and Formula C for nickel-chromium and nickel-iron-chromium alloys.

Additional information on preparing surfaces for welding is given in "Joining."[3]

Table 11 - Effect of Cleaning Method on Relaxation of INCONEL alloy X-750 Springs[a]

Cleaning Method	Relaxation, %, in 250 h at 60 000 psi (414 MPa) and 1000 °F (540 °C)
No Cleaning, As-Age-Hardened	10.0
Oxidizing Salt Bath Plus Formula C	11.5
Tumbling in Sand and Oil	12.8
Abrasive Blasting (120 Grit with Water)	13.3
Shot Peening	13.5
Abrasive Blasting (Standard Sand, Dry)	14.6

[a]Cold-drawn (No. 1 temper) and age-hardened 1350°F (730°C)/16 h.

Introduction

The nickel alloys can be ground, polished, buffed, or brushed by all methods commonly used for other metals. Mechanical finishing operations are discussed in this section.

As with other metals, a series of operations is required to produce a finish on the high-nickel alloys. The number and type of operations required depend on the initial finish of the material, the desired final finish, and the type of equipment used.

Pressures and speeds of the finishing equipment must be closely controlled. The high-nickel alloys, particularly the INCONEL and NIMONIC nickel-chromium and INCOLOY nickel-iron-chromium alloys, do not conduct heat away as rapidly as copper and aluminum. Excessive heat will destroy the true color of the metal and may warp flat, thin articles.

Some general recommendations for finishing operations are given in Table 12.

Table 13 lists spindle speeds and corresponding surface speeds for various wheel diameters.

Table 12 — Recommended Finishing Procedures

Operation	Wheel	Grit No.	Compound	Speed	
				sfpm	m/s
Grinding	Rubber Bond	24 or 36	None	8000 to 9000	40 to 45
Grinding	Vitrified Bond	24 or 36	None	5000 to 6000	25 to 30
Roughing	Cotton Fabric, Sewn Sections	60 or 80	None	6000 to 7500	30 to 40
Dry Fining	Cotton Fabric, Sewn Sections	100 or 120	None	6000 to 7500	30 to 40
Greasing	64-68 Unbleached Sheeting, Spirally Sewn Sections	150 or 180	Polishing Tallow or No. 180 Emery Grease Cake	6000 to 7500	30 to 40
Grease Coloring	88-88 Unbleached Sheeting, Spirally Sewn or Loose Disc; or Quilted Sheepskin	200 or 220	Polishing Tallow or "F" Emery Grease Cake	6000 to 7500	30 to 40
Bobbing and Sanding	Leather Wheel—for two bobbing operations, second with Medium-Density Felt Wheel	-	Grout	5000	25
Cutting Down	88 Unbleached Sheeting, Loose Spirally Sewn Sections or Loose-Disc Wheel	-	Tripoli	8000 to 9000	40 to 45
Coloring (Bright Finish)	88-88 Unbleached Sheeting, Loose Spirally Sewn Sections or Loose-Disc Wheel	-	White Aluminum Oxide	10 000	50
Coloring (Mirror Finish)	Loose-Disc, 88-88 Unbleached Sheeting or Canton Flannel	-	Green Chromium Oxide	10 000	50
Brushing	Tampico	-	"F" Emery Grease Cake or Grout	1200 to 3000	5 to 15

Table 13— Spindle Speed, rpm, for Various Surface Speeds and Wheel Diameters

Surface Speed		Wheel Diameter, in. (mm)						
fpm	m/s	6 (15)	8 (203)	10 (254)	12 (305)	14 (356)	16 (406)	18 (457)
3000	15	1930	1450	1150	950	820	710	640
4000	20	2550	1900	1500	1300	1100	950	850
5000	25	3200	2400	1900	1600	1375	1200	1050
5500	28	3500	2600	2100	1750	1500	1300	1175
6000	30	3800	2850	2300	1900	1650	1425	1275
7500	38	4800	3550	2850	2400	2100	1800	1600
8000	41	5100	3800	3100	2550	2200	1900	1700
9000	46	5750	4300	3450	2850	2450	2150	1900
10000	51	6400	4750	3800	3200	2750	2400	2100

Grinding

Grinding is often the first operation in a finishing sequence. Grinding is used to remove large surface imperfections and to rough-down welds prior to polishing and buffing.

Rubber-bond grinding wheels are recommended for the Nickel and MONEL nickel-copper alloys. These wheels are used for their cutting effectiveness and for their relative softness, which reduces the heat generated. Rubber-bond wheels should be operated at a surface speed of 8000 to 9000 fpm (40 to 45 m/s).

Vitrified-bond wheels are preferred for grinding the harder alloys such as the INCONEL and INCOLOY alloys. These wheels should be operated at a surface speed of 5000 to 6000 fpm (25 to 30 m/s).

Light welds can be ground efficiently with a No. 36 grit wheel. For heavy welds a No. 24 grit is more practical.

Additional information on grinding operations is given in "Machining."[4]

Polishing

The first polishing operation should be done with the finest grit that will remove all surface defects and give a base upon which to build the final finish. Wheels of No. 60 to No. 80 grit are usually required to remove heavy oxide or deep defects.

The first operation should be done dry. After the initial roughing, tallow should be used on all roll-head wheels of No. 150 grit or finer. Tallow clogs the wheel and gives a smoother finish, and also reduces the amount of heat generated.

For polishing flat work, each subsequent polishing operation should be done with a grit 30 to 40 numbers finer than the previous one, until the surface is suitable for a brushing or bobbing operation to prepare for buffing.

When possible, the scratches produced by the abrasive should cross the scratches left by the preceding operation. When polishing is done in only one direction, the finer abrasive will follow in the grooves made by the coarser abrasive, impairing the efficiency of the polishing wheels.

Wheels for roughing and dry fining should be made of tightly woven, unbleached cotton fabric. To prevent chattering, the wheels should be perfectly balanced and should have a soft or cushioned face. Fine grit wheels require more cushions than coarse wheels.

A more resilient and flexible wheel should be used for greasing operations. Greasing wheels should be made of 64-68 count, unbleached sheeting and should have more cushion than the wheels used for coarser polishing.

Grease coloring may be done on a full-disc, quilted sheepskin wheel or a spirally sewn wheel made of fine-count (88-88) heavy sheeting.

Compounds of artificial abrasives are preferred for roughing and dry-fining. Turkish emery is usually used for greasing and grease coloring.

Bobbing done with emery grout is more on the order of burnishing than polishing and, if performed in one operation, is best done with leather wheels. If bobbing is done in two operations, the second should be done with a medium-density felt wheel. Less pressure is required with felt than with leather wheels.

The best results are obtained from emery roll-head wheels at surface speeds of 6500 to 7500 fpm (33 to 38 m/s). The metal drags at slower speeds; at excessive speeds the wheel tends to pull up the surface of the metal.

Buffing

A high-quality wheel of the proper construction and material is essential for good results in buffing. Wheels should be of sturdy, closely woven, high-count sheeting. Close weaves give good cutting, and heavy threads give good coloring.

Buffing is usually done in two operations. The first or cutting-down operation is done with a sewn buffing wheel operating at a surface speed of 8000 to 9000 fpm (40 to 45 m/s). The second or coloring operation is done with a loose-disc wheel operating at a surface speed of approximately 10 000 fpm (50 m/s). A loose-disc, Canton-flannel wheel is best for buffing to a mirror finish.

The high speeds used in buffing create a high heat. Consequently, less pressure must be used than for polishing.

The cutting-down operation is normally performed with tripoli compound. This compound leaves a haze on high-nickel alloys. A buffing compound with less grease is necessary to promote deep color.

White aluminum oxide and green chromium oxide compounds are recommended for the final coloring. Chromium oxide compounds produce less friction and give a truer color.

Brushing

A brushed finish can be produced on the high-nickel alloys with either a tampico or wire wheel. Tampico wheels usually produce a better finish and higher luster, and, because of their flexibility, are better for irregular shapes. A tampico wheel is used with emery paste or grout to produce a satin finish, and with pumice and water or pumice and oil to produce a butler finish. For wet brushing, tampico wheels should have wooden hubs.

Wire brushes can be used to produce a satin finish on sheet-metal articles. Brushes should have a wire diameter of 0.004 to 0.008 in. (0.10 to 0.20 mm). Steel and brass wire should not be used for brushes used on nickel alloys. Small particles from the brush are always embedded in the metal during brushing. The steel particles will rust and the brass particles will discolor the nickel alloys.

Brushing is done at slower speeds than those used for polishing. Brushing speeds are normally 1200 to 3000 fpm (5 to 15 m/s), depending on the final finish desired. Higher speeds—4000 to 6000 fpm (20 to 30 m/s)—are required to produce a bright wire-brush finish. Wire brushes operated at too slow a speed produce coarse, undesirable scratches.

Appendix

References

[1]"Standard Specifications for Fuel Oils," Standard D-396-80, 1980 *Book of ASTM Standards*, Part 23, 1980. American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania 19103.

[2]N. Bredzs and C. C. Tennenhouse, "Metal-Metal Oxide-Hydrogen Atmosphere Chart for Brazing or Bright Metal Processing." Welding Journal, Vol. 49, No. 5, "Welding Research Supplement," pp. 189s-193s.

[3]"Joining." **Special Metals Corporation** Huntington, West Virginia 25720.

[4]"Machining." **Special Metals Corporation** Huntington, West Virginia 25720.

Nominal Chemical Composition,[a] %, of Representative Alloys

Designation	Ni	C	Mn	Fe	S	Si	Cu	Cr	Al	Ti	Others
Nickel Alloys											
Nickel 200	99.5[b]	0.08	0.2	0.2	0.005	0.2	0.1	-	-	-	-
Nickel 201	99.5[b]	0.01	0.2	0.2	0.005	0.2	0.1	-	-	-	-
Nickel 205	99.5[b]	0.08	0.2	0.1	0.004	0.08	0.08	-	-	0.03	Mg 0.05
DURANICKEL alloy 301	96.5[b]	0.2	0.2	0.3	0.005	0.5	0.1	-	4.4	0.6	-
MONEL Nickel-Copper Alloys											
MONEL alloy 400	66.5[b]	0.2	1.0	1.2	0.01	0.2	31.5	-	-	-	-
MONEL alloy 404	54.5[b]	0.08	0.05	0.2	0.01	0.05	44.0	-	0.03	-	-
MONEL alloy R-405	66.5[b]	0.2	1.0	1.2	0.04	0.2	31.5	-	-	-	-
MONEL alloy K-500	66.5[b]	0.1	0.8	1.0	0.005	0.2	29.5	-	2.7	0.6	-
MONEL Copper-Nickel Alloy											
MONEL alloy 450	31	—	0.5	0.7	—	—	67	-	-	-	-
INCONEL Nickel-Chromium Alloys											
INCONEL alloy 600	76.0[b]	0.08	0.5	8.0	0.008	0.2	0.2	15.5	-	-	-
INCONEL alloy 601	60.5	0.05	0.5	14.1	0.007	0.2	0.5	23.0	1.4	-	-
INCONEL alloy 617	52.0	0.07	0.5	1.5	0.008	0.5	0.2	22.0	1.2	0.3	Co 12.5 Mo 9.0
INCONEL alloy 625	61.0[b]	0.05	0.2	2.5	0.008	0.2	-	21.5	0.2	0.2	Mo 9.0 Cb+Ta 3.6
INCONEL alloy 690	61	0.02	0.2	9	0.008	0.2	0.2	29	-	-	Co 0.05
INCONEL alloy 718	52.5	0.04	0.2	18.5	0.008	0.2	0.2	19.0	0.5	0.9	Mo 3.0 Cb + Ta 5.1
INCONEL alloy X-750	73.0[b]	0.04	0.5	7.0	0.005	0.2	0.2	15.5	0.7	2.5	Cb+Ta 1.0
INCONEL alloy 751	72.5[b]	0.05	0.5	7.0	0.005	0.2	0.2	15.5	1.2	2.3	Cb+Ta 1.0
INCOLOY Nickel-Iron-Chromium Alloys											
INCOLOY alloy 800	32.5	0.05	0.8	46.0	0.008	0.5	0.4	21.0	0.4	0.4	-
INCOLOY alloy 802	32.5	0.4	0.8	46.0	0.008	0.4	0.4	21.0	-	-	-
INCOLOY alloy 825	42.0	0.03	0.5	30.0	0.02	0.2	2.2	21.5	0.1	0.9	Mo 3.0
NI-SPAN-C alloy 902	42.2	0.03	0.4	48.5	0.02	0.5	0.05	5.3	0.6	2.6	-
INCOLOY Nickel-Iron-Cobalt Alloy											
INCOLOY alloy 903	38.0	-	-	50	-	-	-	-	0.7	1.4	Co 15.0 Cb 3.0
NILO Nickel-Iron Alloys											
NILO alloy 36	36	-	-	64	-	-	-	-	-	-	-
NILO alloy 42	42	-	-	58	-	-	-	-	-	-	-
NIMONIC Nickel-Chromium Alloys											
NIMONIC alloy 75	76	0.1	0.5	2.5	-	0.5	0.2	19.5	-	0.4	-
NIMONIC alloy 80A	73	0.05	0.5	1.5	0.008	0.5	0.1	19.5	1.4	2.2	Co 1
NIMONIC alloy 90	56.5	0.06	0.5	0.75	0.008	0.5	0.1	19.5	1.5	2.5	Co 18
NIMONIC alloy 105	52	0.06	0.5	0.5	0.008	0.5	0.1	15	4.7	1.2	Co 20, Mo 5
NIMONIC alloy 115	56	0.16	0.5	0.5	0.008	0.5	0.1	15	5.0	4.0	Co 14, Mo 4
NIMONIC alloy 263	50	0.06	0.3	0.4	0.004	0.2	0.1	20	0.3	2.2	Co 20, Mo 6

[a]Not for specification purposes.
[b]Includes cobalt.

Nominal Room-Temperature Mechanical-Property Ranges[a]

Material	Form	Condition	Tensile Strength		Yield Strength (0.2% Offset)		Elong., %	Rockwell Hardness
			10^3 psi	MPa	10^3 psi	MPa		
Nickel 200	Sheet	Annealed	55-75	379-517	15-30	103-207	55-40	70B max.
	Strip	Annealed	55-75	379-517	15-30	103-207	55-40	64B max.
	Bar	Annealed	55-80	379-552	15-30	103-207	55-40	45B-70B
MONEL alloy 400	Sheet	Annealed	70-85	483-586	25-45	172-310	50-35	73B max.
	Sheet	Cold-Rolled, Hard	100-120	690-827	90-110	621-758	15-2	93B min.
	Strip	Cold-Rolled, Annealed	70-85	483-586	25-45	172-310	55-35	68B max.
	Bar	Annealed	70-85	483-586	25-40	172-276	50-35	61B-76B
MONEL alloy K-500	Sheet	Cold-Rolled, Annealed	90-105	621-724	40-65	276-448	45-25	85B max.
	Bar	Annealed	90-110	621-758	40-60	276-414	45-25	76B-90B
INCONEL alloy 600	Sheet	Cold-Rolled, Annealed	80-100	552-690	30-45	207-310	55-35	88B max.
	Strip	Cold-Rolled, Annealed	80-100	552-690	30-45	207-310	55-35	88B max.
	Bar	Annealed	80-100	552-690	30-50	207-345	55-35	68B-86B
INCONEL alloy 601	All Forms	Solution Treated	75-110	515-760	25-55	160-380	75-40	55B-95B
INCONEL alloy 617	Plate	Hot-Rolled, Solution Annealed	106.5[b]	734[b]	52.3[b]	361[b]	62[b]	87B[b]
	Bar	Hot-Rolled, Solution Annealed	111.5[b]	769[b]	51.5[b]	355[b]	56[b]	88B[b]
INCONEL alloy 625	Sheet	Annealed	120-140	827-965	60-75	414-517	55-30	-
	Bar	Annealed	120-150	827-1034	60-95	414-655	60-30	94B-34C
	Bar	Solution-Annealed	105-130	724-896	42-60	290-414	65-40	86B-25C
INCONEL alloy 690	Strip	Cold-Rolled, Annealed	105.0[b]	724[b]	50.5[b]	348[b]	41[b]	-
	Rod	Hot-Rolled, Annealed	107.0[b]	738[b]	54.0[b]	372[b]	44[b]	88B
INCONEL alloy 718	Bar	Annealed	140[b]	965[b]	85.7[b]	591[b]	46[b]	23C[b]
	Bar	Age-Hardened[c]	185-215	1276-1482	150-185	1034-1276	25-12	
INCONEL alloy X-750	Bar	Age-Hardened[d]	170-206	1172-1420	120-163	827-1124	25-15	34C-44C
INCOLOY alloy 800	Sheet	Annealed	75-105	517-724	30-55	207-379	50-30	88B max.
	Strip	Annealed	75-105	517-724	30-55	207-379	50-30	84B max.
	Bar	Annealed	75-100	517-690	30-50	207-345	50-30	68B-86B
INCOLOY alloy 825	Bar	Annealed	85-105	586-724	35-65	241-448	50-30	68B-89B
INCOLOY alloy 903	Flat	Heat-Treated[e]	190	1310	160	1103	14	41C-44C[b]
NILO alloy 36	Bar	Annealed	71[b]	490[b]	35[b]	240[b]	42[b]	76B[b]
NILO alloy 42	Bar	Annealed	71[b]	490[b]	36[b]	250[b]	43[b]	76B[b]
NIMONIC alloy 75	Sheet	Annealed	122[b]	840[b]	65[b]	450[b]	30[b]	87B[b]
NIMONIC alloy 80A	Sheet	Annealed	116[b]	800[b]	54[b]	375[b]	52[b]	94B[b]
NIMONIC alloy 90	Sheet	Annealed	125[b]	865[b]	67[b]	460[b]	50[b]	99B[b]
NIMONIC alloy 105	Bar	Precipitation Hardened[f]	165[b]	1140[b]	112[b]	775[b]	22[b]	37C-42C
NIMONIC alloy 115	Bar	Precipitation Hardened[g]	184[b]	1270[b]	123[b]	850[b]	27[b]	39C-45C
NIMONIC alloy 263	Sheet	Precipitation Hardened[h]	141	973	84	580	39	—

[a]Not suitable for specification. [b]Typical values.
[c]Annealed 1700° to 1850°F (925° to 1010°C) and aged 1325°F (720°C)/8 h, F.C. to 1150°F (620°C), held for total of 18 h.
[d]Hot-rolled and aged 1300°F (705°C)/20 h.
[e]Heat treated 1550°F (845°C)/1 h, W.Q. + 1325°F (720°C)/8 h, F.C. 100°F (56°C)/h to 1150°F (620°C)/8 h, A.C.
[f]Annealed 2100°F (1150°C)/4 h and aged 1920-1950°F (1050-1065°C)/16 h plus 1560°F (850°C)/16 h, A.C.
[g]Annealed 2175°F (1190°C)/1.5 h and aged 2010°F (1100°C)/6 h, A.C.
[h]Annealed 2100°F (1150°C) and aged 1470°F (800°C)/8 h, A.C.

Formulas for Pickling Solutions

FORMULA				TEMPERATURE	
	Reagents	% Weight (except where otherwise noted)	Amount Added	°F	°C
A	Nitric Acid (HNO_3) 42° Bé Water	20	300 mL 1000 mL	160	70
B*	Nitric Acid (HNO_3) 42° Bé Sodium Chloride (NaCl) Water	10 5	133 mL 63 g 1000 mL	170	75
C	Nitric Acid (HNO_3) 42° Bé Hydrofluoric Acid (HF) 30° Bé Water	20 2	315 mL 34 mL 1000 mL	125	50
D	Sulfuric Acid (H_2SO_4) 66° Bé Water	25	200 mL 1000 mL	180	80
E	Sulfuric Acid (H_2SO_4) 66° Bé Sodium Chloride (NaCl) Water	15 5	111 mL 63 mL 1000 mL	180	80
F	Sulfuric Acid (H_2SO_4) 66° Bé Sodium Dichromate ($Na_2Cr_2O_7$) Water	15 10	119 mL 135 g 1000 mL	70 - 100	20 - 40
G	Sulfuric Acid (H_2SO_4) 66° Bé Sodium Fluoride (NaF) Water	12 2	82 mL 23 g 1000 mL	Ambient	Ambient
H	Sulfuric Acid (H_2SO_4) 66° Bé Sodium Chloride (NaCl) Sodium Nitrate ($NaNO_3$) Water	20 5 5	171 mL 73 g 73 g 1000 mL	180	80
I	Sulfuric Acid (H_2SO_4) 66° Bé Nitric Acid (HNO_3) 42° Bé Sodium Chloride (NaCl) Water	35 30 0.5	1200 mL 1860 mL 30 g 1000 mL	70 - 100	20 - 40
J	Hydrochloric Acid (HCl) 20° Bé Water	6	200 mL 1000 mL	140	60
K	Hydrochloric Acid (HCl) 20° Bé Cupric Chloride ($CuCl_2$) Water	12 2	535 mL 33 g 1000 mL	180	80
L	Hydrochloric Acid (HCl) 20° Bé Ferric Chloride ($FeCl_3$) Water	1 1	30 mL 11 g 1000 mL	Ambient	Ambient
M	Sodium Hydroxide (NaOH) Potassium Permanganate ($KMnO_4$) Water	15 5	188 g 63 g 1000 mL	180	80
N	Ammonium Hydroxide (NH_4OH) Water	2 (%Volume)	20 mL 1000 mL	Ambient	Ambient
O	Alkaline Cleaner Water		60 to 75 g/L 1000 mL	180	80
P	Agar-Agar Potassium Ferricyanide ($K_3Fe(CN)_6$) Sodium Chloride (NaCl) Water	1 0.1 0.1	10 g 1 g 1 g 1000 mL	70 - 150	20 - 65

*An addition of at least 40 g of nickel per litre to Formula B will prevent overpickling of chromium-bearing alloys.

SPECIAL METALS

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U.S.A.

Special Metals Corporation
Billet, rod & bar, flat & tubular products
3200 Riverside Drive
Huntington, WV 25705-1771
Phone +1 (304) 526-5100
+1 (800) 334-4626
Fax +1 (304) 526-5643

Billet & bar products
4317 Middle Settlement Road
New Hartford, NY 13413 5392
Phone +1 (315) 798-2900
+1 (800) 334-8351
Fax +1 (315) 798-2016

Atomized powder products
100 Industry Lane
Princeton, KY 42445
Phone +1 (270) 365-9551
Fax +1 (270) 365-5910

United Kingdom

Special Metals Wiggin Ltd.
Holmer Road
Hereford HR4 9SL
Phone +44 (0)1432 382200
Fax +44 (0)1432 264030

France

Special Metals Services SA
17 rue des Frères Lumière
69680 Chassieu (Lyon)
Phone +33 (0)4 72 47 46 46
Fax +33 (0)4 72 47 46 59

Germany

Special Metals Deutschland Ltd.
Postfach 20 04 09
40102 Düsseldorf
Phone +49 (0)211 38 63 40
Fax +49 (0)211 37 98 64

Hong Kong

Special Metals Pacific Pte. Ltd.
Room 1110, 11th Floor
Tsuen Wan Industrial Centre
220-248 Texaco Road, Tsuen Wan
Phone +852 2439 9336
Fax +852 2530 4511

India

Special Metals Services Ltd.
520, 46th Cross, V Block
Jayanagar, Bangalore 560 041
Phone +91 (0)80 664 6521
Fax +91 (0)80 664 2773

Italy

Special Metals Services SpA
Via Assunta 59
20054 Nova Milanese (MI)
Phone +390 (0)362 4941
Fax +390 (0)362 494224

The Netherlands

Special Metals Services BV
Postbus 8681
3009 AR Rotterdam
Phone +31 (0)10 451 44 55
Fax +31 (0)10 450 05 39

Singapore

Special Metals Pacific Pte. Ltd.
50 Robinson Road
06-00 MNB Building, Singapore 06888
Phone +65 222 3988
Fax +65 221 4298

Affiliated Companies

Special Metals Welding Products
1401 Burris Road
Newton, NC 28658, U.S.A.
Phone +1 (828) 465 0352
+1 (800) 624 3411
Fax +1 (828) 464 8993

Regal Road
Stratford-upon-Avon
Warwickshire CV37 0AZ, U.K.
Phone +44 (0)1789 268017
Fax +44 (0)1789 269681

Controlled Products Group
590 Seaman Street, Stoney Creek
Ontario L8E 4H1, Canada
Phone +1 (905) 643 6555
Fax +1(905) 643 6614

A-1 Wire Tech, Inc.
A Special Metals Company
840 39th Avenue
Rockford, IL 61109, U.S.A.
Phone +1 (815) 226 0477
+1 (800) 426 6380
Fax +1 (815) 226 0537

Reseal SA
A Special Metals Company
200 rue de la Couronne des Prés
78681 Epône Cédex, France
Phone +33 (0)1 30 90 04 00
Fax +33 (0) 30 90 02 11

DAIDO-*SPECIAL METALS* Ltd.
A Joint Venture Company
Daido Building
7-13, Nishi-shinbashi 1-chome
Minato-ku, Tokyo 105, Japan
Phone +81 (0)3 3504 0921
Fax +81 (0)3 3504 0939

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