- *Vanadium, 0 to 13%:* stabilizes the β phase
- *Molybdenum, 0 to 11%:* stabilizes the β phase
- *Chromium, 0 to 11%:* stabilizes the β phase

Of all of these alloy elements, only aluminum contributes to lowering the density of the alloy. All of the other common alloy elements cause the density to increase and a small price is paid for their usage in terms of extra weight.

The β transus for pure titanium is 910 °C (1675 °F). The α stabilizing elements cause an increase in the β transus temperature, whereas the β stabilizing elements cause the β transus to decrease.

Titanium alloys are often classified into three major categories: α/near-α, β/near-β, and α + β. Each class requires special hot working temperatures and process conditions.

The most common titanium alloys are commercially pure titanium (Ti-CP) which is in the α classification and titanium with 6% Al and 4% V (Ti-6Al-4V or just Ti-6-4) which is an α + β alloy. Unlike steels and aluminum alloys, there is no systematic grade designation for titanium alloys. Titanium alloys are often referenced as Ti- followed by a string of numbers. The numbers indicate the weight percent of various alloying elements. For example, Ti-13-11-3 is titanium with 13% V, 11% Cr, and 3% Al, which is a β alloy with a β transus temperature of 675 °C (1250 °F).

Microstructure. The microstructure of many titanium alloys is a mixture of α and β phases. The hot working temperature and the cooling afterwards have a strong influence on the morphology of the two phases within the microstructure. Each working condition produces different microstructures and hence different properties in the final component.

Applications. Titanium has an excellent combination of high strength, low density, corrosion resistance, and the ability to operate at reasonably high temperatures. Forged titanium alloys are widely used in aerospace applications. Structures benefit from the high strength-weight ratio. Fan and compressors in turbine engines make extensive use of titanium due to the ability to operate at temperatures in excess of 425 °C (800 °F). Chemical and energy applications include valves and risers in offshore drilling. The high strength at lower weight relative to steel makes titanium suitable for these applications. Titanium components are also used in medical applications for prosthetic devices such as knee replacements and surgical fasteners (screws and pins) due to the corrosion resistance and modulus close to that of a human bone. High-performance sport equipment is also made from titanium alloys because of its high strength-weight ratio. High-price golf clubs have titanium heads and high-end bicycles have numerous titanium components.

Hot Deformation of Titanium Alloys. In general, β alloys are easier to work than the α + β alloys and α alloys. Initial deformation temperatures for ingot breakdown are higher than the intermediate working temperatures, which are higher than the finish working temperatures. What is referred to as conventional forging occurs at temperatures below the β transus, usually in the α + β region of the alloy. Beta forging occurs at temperatures above the β transus.

Titanium alloys are more challenging to hot work than most steel and aluminum alloys due to the required process control. Control of the working temperature is essential to achieve good workability and to produce the microstructure required to achieve mechanical properties in service. Temperature is not limited to the furnace set point but must account for adiabatic heating, die chill, and heat loss to the environment. Titanium can rapidly soften at high temperatures and strain rates, resulting in (sometimes severe) flow localization. This type of defect can appear to be a lap or even a forging crack. Thus, it is common to forge titanium at lower strain rates on hydraulic or screw presses. Hammer forging titanium takes extreme care and is uncommon for the most critical applications.

Titanium loses heat to cold dies and the environment faster than steel due to the lower heat capacity and lower density. Thus, best practice in titanium forging requires heated dies or isothermal forging. These forging process are more costly but can provide a better forged product of this high-value material. Hot-die forging and isothermal forging allow a component to be forged closer to its final shape, resulting in lower machining cost and less waste of this expensive material.

Dies may wear quickly when forging titanium, especially when near-net shape features are forged.

When forging titanium above 590 °C (1100 °F) in air, a surface oxide scale can form and the oxygen can diffuse into the component. This surface condition is called α case and it should be removed before the component can be put into service. In many alloys, α case has lower ductility and is subject to moderate-to-severe surface cracking. A range of coatings is commercially available to assist in lubrication and create an oxygen barrier. Control of the coating process—including preheating and surface cleaning—is one more intricacy to be considered, or the coating can be rendered useless.

Processing of Titanium Alloys. It should be noted that both the α + β alloys as well as the β alloys can be heat treated after forging to obtain a variety of strengths. The heat treatment is a two-step process. An initial high-temperature solution treatment is used to form β and a second lower temperature is used to form α in the β matrix. This second step is referred to as an aging step. The heat treatment process is similar to the heat treatment given to aluminum alloys, although higher temperatures are used for titanium alloys.

Titanium alloy components are expensive. The raw material is costly and it takes quite a bit of energy and careful processing to produce a billet suitable for subsequent deformation. Hot working costs are higher due to the required process controls. Machining costs are one to two orders higher than those for machining aluminum.

As in hot working, tool wear during machining is also an issue. Heat generated during machining exceeds that removed by conduction, thus fast coolants are common. Other issues during machining include chemical reactivity, brittle α case, heat generation degrading cutting tools, and a reaction between the hot tools and workpiece surface, all of which result in higher machining cost.

Superalloys

Superalloys are normally nickel-base, although cobalt- and iron-base superalloys have also been developed. There is a significant amount of other alloy elements added to the base. The superalloy systems are very complex, often existing with a large variety of second-phase particles in the base metal matrix. Superalloys are called super because their service conditions in critical applications generally require very high strengths at high temperatures, frequently exceeding 535 °C (1000 °F). In final applications superalloy components have good creep rupture strength and good oxidation resistance, so they are quite suitable for high-temperature applications. Their corrosion resistance makes them suitable for harsh environments, including petrochemical components.

Chemistry and Grades. Nickel-base superalloys are comprised of 50 to 78% Ni. Other major alloying elements in these complex systems include:

- *Chromium, 14 to 23%:* provides solid-solution strengthening and forms carbides
- *Molybdenum, 0 to 18%:* provides solid-solution strengthening and forms carbides
- *Tungsten, 0 to 5%:* provides solid-solution strengthening and forms carbides
- *Iron, 3 to 20%:* provides strengthening
- *Cobalt, 0 to 5%:* provides solid-solution strengthening and raises the melting point
- *Titanium, 0 to 6%:* forms precipitates

The superalloy metallurgist has used a large number of the metals in the periodic table in creating these alloys.

The alloy grade designation is not systematic as with iron alloys or aluminum alloys. The numbering scheme does have a small amount of information that can be extracted from it. For example, the 6*xx* (where *x* stands for another number) alloys are composed of nickel plus chromium plus other elements. The 7*xx* alloys are composed of the same nickel plus chromium plus other elements but are strengthened by precipitation hardening. The C-*xxx* alloys are composed of nickel, chromium, molybdenum plus other elements.

The most common superalloy seems to be alloy 718, often called Inconel 718 or simply Inconel.

The latter names occur because the alloy was first developed by International Nickel and the Inconel designation is a registered trademark.

Microstructure. The 7*xx* series of superalloys supplement strength by very fine precipitates called γ'. Because the base nickel is face-centered cubic (fcc), the structure is often referred to as γ or sometimes as austenite. During hot deformation recrystallization can start at the prior grain boundaries, but if there is not enough deformation to cause complete recrystallize, then a duplex grain structure may occur. The duplex structure will have recrystallized grains outlining the prior grains. This outlined structure is called a necklace microstructure because the new small grains surrounding the larger prior grains look like a necklace. Although interesting to observe, the properties of such structures are often not the best.

The 6*xx* series forms essentially a single-phase fcc phase that gets its strength from the other elements by solid-solution strengthening and by deformation at temperatures below the recrystallization temperature for the alloy. A microstructure of these alloys consists of a single-phase material with grain boundaries.

It should be noted that other alloying elements in these superalloys can form other precipitates such as a variety of different carbides or intermetallic compounds. These precipitates can be beneficial at times but are often somewhat detrimental by decreasing the creep resistance during use.

Applications. Superalloys are used in components that are exposed to temperatures of 650 to 980 °C (1200 to 1800 °F). Components such as turbine disks, cases, shafts, and blades require superalloys because the higher temperature is required to increase aircraft performance and fuel efficiency. Superalloy fittings, pipe, and valves are used at high temperatures in corrosive environments. Because of their corrosion resistance, superalloys are also used as pins and replacement joints in medical applications. Because a number of people have an allergic reaction to nickel, the superalloys for medical components are often cobalt-base rather than nickel-base.

The operating range of superalloys is much higher as compared to any of the other alloy systems discussed in this article. It also is of interest to note that the high end of the operating range begins to impinge on the low end for the hot working region.

Hot Deformation of Superalloys. In most alloy systems, the forge shop is responsible to produce a shape, with mechanical properties obtained by heat treatment. Conversely, superalloys obtain strength from their base chemistry, secondary particles (controlled by heat treatment), and grain size. Fine grains are required to meet most commercial and military specifications. Unfortunately, the grains are always growing when in a hot environment such as preheating for forging or heat treatment. Thus, temperature control during forming is critical to ensure that there is the proper amount of deformation imparted at a temperature where recrystallization can occur but where grain growth is limited.

The flow stress for superalloys is higher relative to any other common hot worked metal. Cold forming of fasteners and pins is common in alloy and stainless steels. When deploying precision cold forming to superalloys, preheating to 150 °C (300 °F) is almost always performed prior to deformation.

The hot working of superalloys is very challenging. There is usually a very narrow temperature range to forge a given alloy. The high flow strength also makes them resistant to movement, thus it is difficult to fill detailed die cavities in a closed die without extreme forging pressure. The rules for sizing presses and hammers to produce steel parts are inadequate. Forging superalloys on undersized forging equipment can pose an insurmountable challenge. Smaller equipment results in more hits on a hammer or inadequate deformation in the final forging operation on a press. This type of processing generally results in incomplete recrystallization, thus inadequate strength. Raising the temperature helps with die fill and recrystallization, but grain growth in the heating furnace can offset any gains.

Because of their high flow strength at high temperatures, the forger should anticipate poor tool life when forging superalloys. Numerous examples have been reported of catastrophic die fracture after a handful of forging cycles. Even when the tooling is strong enough to avoid a low-cycle fatigue failure, tool wear is extreme relative to forging other metals. In many applications superalloys are used as die material. It is also common for companies to coat the workpiece to supplement existing lubrication processes, which can easily break down at the required forging pressures.

Heat Treatment. For the precipitation-hardenable superalloys a three-step heat treatment is given after forging. The first step is a high-temperature solution treatment followed by a quench. The second step is a precipitation treatment at a temperature below the solution temperature. This step produces the γ' precipitates. The third step is a second precipitation treatment at a temperature lower than the first precipitation step. During this third step additional finer precipitates are formed. Thus, not only is the alloy composition complex, but also the postforging heat treatment processing is more complicated than most other alloy systems.

Special Considerations. It should be noted that these alloys are not only challenging to hot work, they are often difficult to machine and to weld. Hence the postworking operations require careful adherence to proper procedures.

Like some stainless steels, a number of the superalloy systems are susceptible to sensitization. Sensitization occurs when some grain-boundary precipitates form on cooling, robbing the adjacent regions of alloy content (primarily chromium). These alloy-depleted regions next to the grain boundaries are prone to corrosion attack or to oxidation. To avoid these undesirable properties in the component, the alloy needs to be quickly cooled through the sensitization temperature range.

For the non-precipitation-hardenable alloys, their strength is obtained by deformation. For these systems it is imperative to strictly follow the heating and deformation schedules during hot working.

Copper Alloys

Copper in the pure form is very soft so alloy elements are normally added to increase the strength. When zinc is added to copper it is commonly called brass. Bronze is another copper alloy with the addition of tin. Cupronickels are, as their name implies, copper-nickel alloys. Alloys of copper with large amounts of nickel are called Monel. Aluminum bronzes are alloys of copper with aluminum and iron. In each case the alloy is much stronger than pure copper.

Copper is an excellent conductor of both heat and electricity, with outstanding corrosion properties. The vast majority of electrical wire and connectors are copper, which exhibits very low resistance relative to any other metal of a similar cost. Small electrical connectors are typically cold formed, with larger connectors frequently being hot formed, especially in high-current and power transmission applications. The high thermal conductivity makes copper alloys ideal for heat exchangers and heating components where thermal efficiency is critical. Welding tips are almost always copper, due to the requirement for thermal and electrical conductivity without corrosion. These are generally cold formed. The excellent corrosion resistance makes copper an ideal roofing material. Brass padlocks are used by utilities and refineries in outdoor applications. The shackle and lock bodies are forged (or extruded). Copper pipe, tubing, valves, faucets, and fittings are used in a wide range of water and steam systems, especially drinking water. Marine applications include seawater piping, fittings, valves, and some structural applications, many of which are forged or extruded.

Copper roofs and statues made from copper alloys develop with time a blue-greenish color called a patina, which provides for good corrosion resistance.

The machinist is usually pleased when a cooper or a copper alloy is selected for fabrication of a part, because copper alloys have very good machinability.

The golden color of copper alloys is often very appealing and hence many artistic items are made from copper alloys without the expense of using gold.

Chemistry and Grades. Copper alloys are strengthened by either solid solution or by precipitation hardening. For the alloys that have solid solution as the primary strengthening mechanism, copper-zinc alloys or brasses are most common. The single-phase α brasses are alloys of copper with up to 32% Zn. These alloys can also be strengthened by cold work. An unusual property of these α brasses is that in some cases an alloy with additional zinc is both stronger and more ductile than a leaner alloy. The α-β brasses are two-phase metals with between 32 and 40% Zn.

Bronzes with up to 10% Sn are not normally hot worked but produced by casting. The aluminum bronzes with up to 10% Al and 4% Fe plus small additions of other elements excluding tin are fairly forgeable. Hot-workable cupronickels contain up to 30% Ni.

The highest-strength copper alloys are the copper-beryllium alloys that are precipitation strengthened. These alloys contain up to 2% Be and must be handled with care. They can reach strengths over 1380 MPa (200 ksi) and are often used in electrical contacts where high strength is required.

Microstructure. Alpha brasses are a single-phase material. These alloys can exhibit a number of annealing twins that are seen as the straight lines from one side of the grain to the other. The cold formed copper alloys show significant grain distortion and possess higher strength than the annealed brass.

Applications. Forged copper and brass alloys are used in electrical components, decorative applications, and corrosion-resistant components. Copper tubing and sheet are very common for heat transfer applications.

Hot Deformation of Copper Alloys. Copper and copper alloys exhibit good ductility, thus are generally considered easy to work. When hot working, the preheat temperature typically ranges between 730 and 925 °C (1350 and 1700 °F).

The most hot-workable copper alloy is one with 38% Zn and a small amount of lead. At room temperature this alloy is a two-phase α-β brass; the hot working temperatures transform the alloy into the single-phase β region where deformation occurs easily. Lubrication requirements are generally minimal because the copper oxide that forms on the surface is a natural lubricant.

Copper and copper alloys can be cold forged. Cold forging is especially useful for small-sized components that can be formed to net shape with tight tolerances. Cold forging also adds cold work to the component and hence increases its strength. The caveat is that the work hardening in copper alloys is more pronounced than in most metals, with increasing flow stress and eventual fracture after excessive cold work.

When forging copper-beryllium alloys, they must be handled with care and the operators need to use appropriate safety equipment because beryllium is toxic and can cause severe lung problems (e.g., berylliosis or chronic beryllium disease).

Processing After Hot Deformation. The beryllium coppers can be heat treated in a similar fashion to the precipitation-hardenable aluminum alloys. They are heated to a high temperature called solution treatment to dissolve all of the alloying elements and form a single-phase structure. They are then quenched to room temperature, which locks in the single-phase microstructure. In the final step they are given another heat treatment that is lower than the solution temperature, where a very fine second-phase solid-state precipitation occurs, leading to the marked increase in strength. This last heat treatment is called aging.

If the copper alloy is cold forged its strength is increased but its ductility may be too low for the intended application. The ductility of these alloys is re-established by an annealing heat treatment; however, the strength decreases.

Special Considerations. It should be noted that pure copper is easy to forge. The α-β brasses are also easy to forge, especially in the β-phase temperature region. The α brasses can be hot forged but are more difficult. The aluminum bronzes are also forgeable but challenging. The copper-nickel alloys have higher forging temperatures as compared to the other alloys.

An interesting side note about copper alloys is that in ancient times many of the copper ores that were smelted contained arsenic and hence the copper alloys contained this poison. Early signs of arsenic poisoning are the loss of muscle control and appearing "crazy." It is likely that the Greek god of metalworking, Hephaestus, who is often portrayed with a limp and drool coming down from his mouth, is indicative of early Greek metalsmiths, who had been poisoned.

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V. Rudnev and G.E. Totten, editors

Carbon Steels and Alloy Steels Used in Warm and Hot Working

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A DETAILED DESCRIPTION of the steels used in forging and other warm and hot working processes is provided in *ASM Handbook*, Volume 14A, *Metalworking— Bulk Forming*. This article focuses on the specific features of steels that are pertinent to heating by induction for these metal forming processes. Some trends in steel usage are also presented, as well as details about temperature and compositional issues that should be considered in forging of steels that are induction heated.

Induction heating is an attractive process for heating of steels because the ability to rapidly heat material can result in shorter processing times and potential energy savings. Induction heating is often implemented to provide precise, repeatable heating. Industrial thermal cycles are often designed with the intention of minimizing heating time and producing microstructures with adequate, although not necessarily ideal, properties for forging and hot working. Additionally, when a specific location in a billet is examined, the real thermal cycle experienced at various locations in the induction heated volume of the material can vary significantly, particularly as a function of depth below the surface, but also as a function of location relative to the induction coil/induced magnetic field. The variability in the initial material condition is then added to the wide range of thermal cycles, resulting in wider tolerances of precision and repeatability than is desired for a given process.

Modern induction heating processes are capable of rapidly supplying a precise amount of energy to a specific volume of material for a controllable amount of time, which results in heat treatments that are repeatable and provide precise properties in specific locations (Ref 1, 2). However, the design of induction heat treating cycles has until recently been performed largely by trial and error and through the knowledge of experienced coil and process designers. Modern numerical software has made strides in coupling the electromagnetic and thermal phenomena that take place in induction heating, and industrial processes are now designed that benefit from these computational advancements (Ref 3).

Induction heating cycles are designed to supply a precise amount of power to a specific location on a component for a short period of time (Ref 1). Required power input results in a thermal cycle that is affected by temperature of the part and the electrical and magnetic properties of the material as a function of temperature. The heating rate for induction heating thermal cycles generally decreases as a function of material temperature, simply because a specific temperature increase requires more energy at higher temperature, experiences greatly increased surface heat loss through radiation and convection, and is further reduced by a local maximum in specific heat near the Curie temperature (Ref 1, 4).

Microstructural Effects on Induction Heating of Steels

At room temperature, induction heating for steel, which is ferromagnetic, occurs as a result of eddy current and hysteresis losses. On heating, steel undergoes a change from ferromagnetic to paramagnetic at the Curie temperature—approximately 768 °C (1414 °F) for iron-carbon alloys below ~0.45 wt% C, equivalent to the Ac_1 temperature; 727 °C (1341 °F) for hypereutectoid compositions; and following the Ac_3 temperature between 0.45 and 0.78 wt% C (Ref 5, 6)—above which the electrical resistance to eddy current flow is dramatically reduced and heat losses increase. As a result, the hysteresis component of induction heating is lost, which results in lower heating rates for a given power input (Ref 1, 6). Hence, the heating rate is much higher at low temperatures than it is at high temperatures. This heating rate variation is especially important because the on-heating phase transformation to austenite also initiates at similar high temperatures (which are dependent on heating rate), resulting in lower heating rates in the region where the phase transformations critical to steel processing occur.

In order to hot or warm form steels, it is necessary to heat the billet into the austenite region. Two of the major variables to consider when designing an induction heating cycle are the heating rate/maximum temperature combination and the scale and type of the prior microstructure, because both will affect the degree of austenitization and therefore the final properties of the component.

Many studies have been performed to experimentally evaluate the austenitization process for steels using various compositions, microstructures, heating rates, and heating methods. Some of the most comprehensive are the studies of Orlich et al. (Ref 7, 8), who evaluated the austenitization kinetics of a wide range of steel alloys as a function of heating rate. Time-temperature-austenitization (TTA) diagrams were developed for a variety of steels using dilatometry. Figure 1 is an example of one such diagram.

The phase transformation temperatures are labeled "Ac," which indicates on-heating transformation*, with a subscript indicating the transformation type. The subscript 1 refers to the initiation of the transformation of ferrite + carbide to ferrite + austenite (for hypoeutectoid steels) or ferrite + carbide to carbide + austenite (for hypereutectoid steels). The subscript 2 refers to the Curie temperature in all cases. The subscript 3 indicates the completion of the ferrite + carbide to austenite + carbide transformation (and leaving the ferrite + austenite phase field) for hypoeutectoid steels. The subscript c indicates the temperature at which all of the carbides are completely dissolved. It should be noted that the uncertainty associated with all of the Ac transformation temperatures can be significant, and this uncertainty generally increases with heating rate. On average, the uncertainty associated with the transformation temperatures from the Orlich study is on the order of ±10 °C, ±18 °F (Ref 7, 8). This value can be as low as

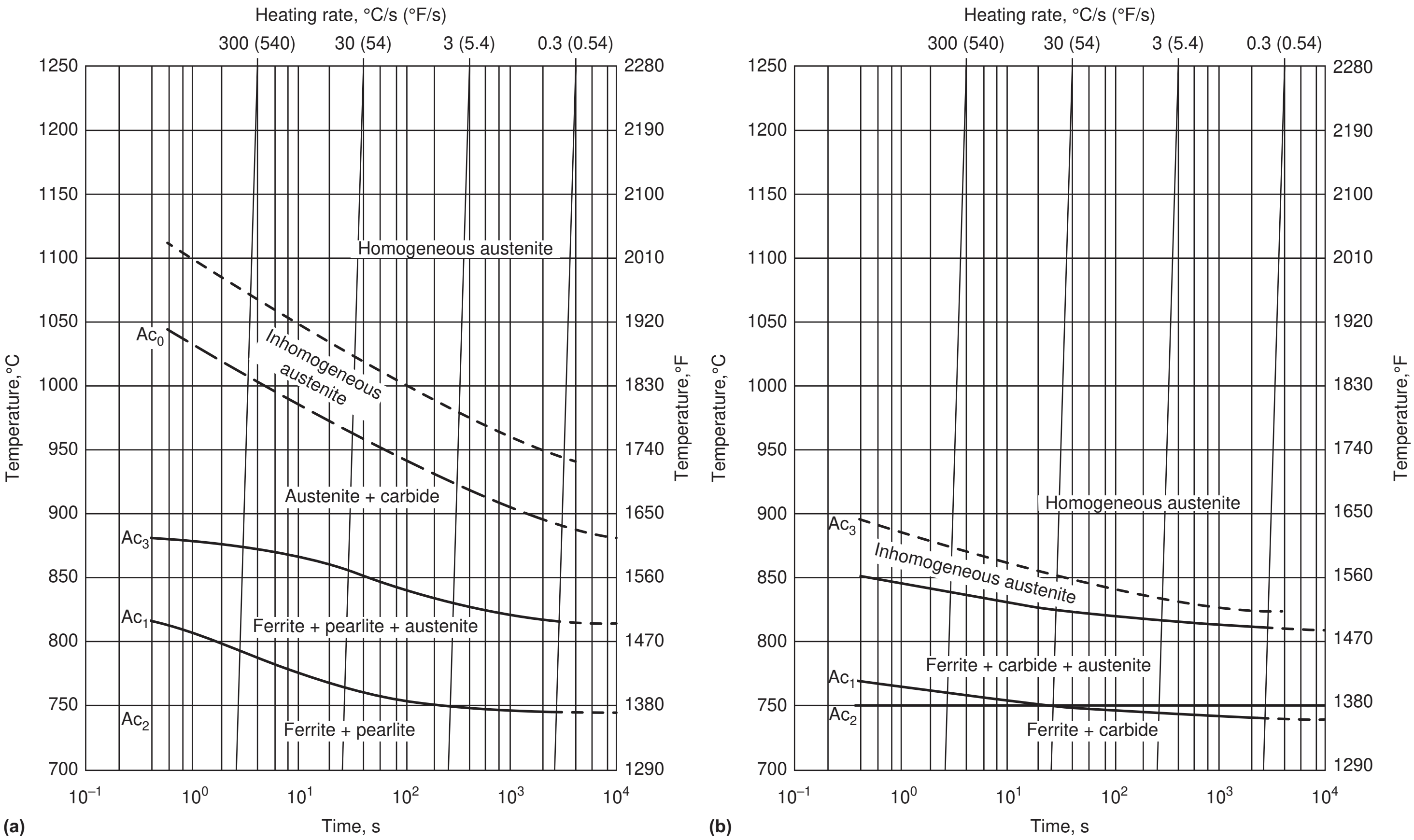

Fig. 1 Time-temperature-austenitization diagrams for (a) 46 Cr 2 with a ferrite + pearlite prior microstructure and (b) 41 Cr 4 with a quenched and tempered microstructure. These steels each have a composition similar to AISI 5150. Source: Ref 8

±5 °C (±9 °F) for Ac_1 and low heating rates, and as high as ±25 °C (±45 °F) for Ac_c temperatures at high heating rates (Ref 7, 8).

Ac indicates an on-heating transformation and is derived from the French *arrêt chauffant* (arrest on heating). Ar indicates an on-cooling transformation, from the French *arrêt refroidissant* (arrest on cooling). Ae or simply A generally indicates an equilibrium transformation temperature (Ref 6).

The region labeled "Inhomogeneous austenite" indicates that the microstructure has been fully transformed to austenite, but gradients in composition exist. These composition gradients are evened out by the time the sample reaches the homogeneous austenite region.

While many studies have focused on the effect of heating rate on austenitization kinetics, relatively few have experimentally examined the effect of prior microstructure on the response to heat treatment, especially at induction heating rates. Figure 1 shows an example of a change in austenitization kinetics as a function of microstructure, where the two compositions are very similar but the microstructures are very different. The finer quenched and tempered martensite prior microstructure has a different TTA diagram than the coarser ferrite + pearlite prior microstructure. Small differences are observed for the Ac_1 and Ac_3 temperatures at higher heating rates. The biggest difference is the time/temperature it takes to fully homogenize the austenite for the ferrite + pearlite prior microstructure, which is significantly higher than for the quenched and tempered prior microstructure.

A study that directly examined the differences between prior microstructures during induction heating was performed by Misaka et al. (Ref 9), and is used here as an example for examining the effects of various prior microstructures on austenitization kinetics, specifically for AISI 1045 steels. For a given composition, it is intuitive that the scale of the microstructure affects the response to heating, because diffusion is required to transport alloying elements through the material. Generally, a coarser microstructure requires longer time or higher temperature to fully austenitize the material, as a result of longer diffusion distances to form homogenous austenite. For an AISI 1045 material, Misaka et al. varied the prior microstructure, producing materials with the following prior microstructures: (a) quenched and tempered, (b) 20 vol% ferrite + pearlite, (c) 32 vol% ferrite + pearlite, (d) 45 vol% ferrite + pearlite, and (e) ferrite + spheroidized cementite. Although no quantitative details of the microstructures are given, it is likely that the quenched and tempered microstructure is the finest (i.e., shortest diffusion distances) and the spheroidized microstructure is the coarsest (i.e., longest diffusion distances).

Figure 2 shows a plot of austenitizing temperature (Ac_3) versus heating time for each of the five initial microstructures. The method for determining these temperatures is not explicitly stated for the Misaka study; however, it is likely that optical microscopy was used to determine which maximum heat treating temperature was required to produce a fully martensitic as-quenched microstructure, because the experiments were performed by surface-hardening gears. In Fig. 2, the Misaka results are also compared with the Ac_3 temperature determined via dilatometry for a Ck 45 steel (Ref 8, 9). The Ac_3 temperature in Fig. 2 indicates the required maximum temperature for complete dissolution of cementite and transformation of ferrite to austenite for a given heating time. Increasing the scale of the microstructure is shown to significantly affect the maximum temperature required to completely transform the prior microstructure to austenite, for a given composition and heating rate.

Considerations for Induction Heating Various Steel Alloys

Material Condition. For surface heat treating, the steels that are induction hardened (such as gears or shafts, among others) are generally in the wrought condition and have a microstructure that has been heavily worked to achieve full density and minimize effects of inclusions. This type of material is ideal for induction heating. For as-cast pieces, powder metallurgy parts, or even wrought material with insufficient reduction ratios, however, any structural irregularities—such as pores, sand defects, or large inclusions—have a significant effect on the local currents imparted by induction heating and may require lower heat intensity, especially at lower temperatures, to avoid localized overheating. Localized overheating may result in stress concentration, cracking, and localized hardness variations (Ref 6). These structural irregularities and defects can also affect performance during quenching, where internal stresses can be quite high and result in cracking during severe quenching. It may be beneficial to reduce the severity of quench for materials that are likely to have significant casting defects.

The hardness of steel should also be considered when performing induction heat treatments, especially those that focus on surface hardening, because thermal gradients can result in significant thermal expansion stresses. On heating, these stresses may be enough to cause significant strain and result in cracking for high-carbon steels in brittle, high-hardness conditions. As a result, it may be advantageous to slow the initial low-temperature heating rate to reduce the thermal gradient and therefore the susceptibility of the material to cracking (Ref 6).

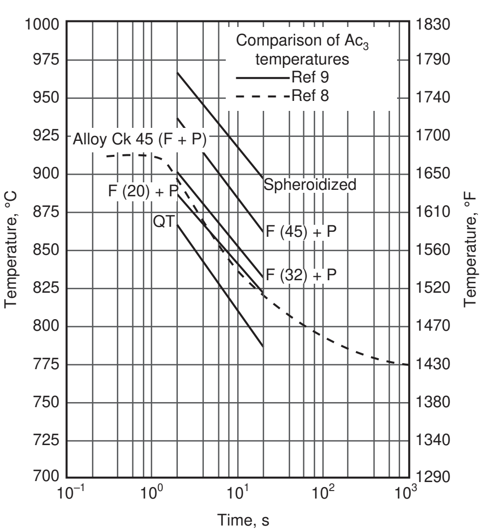

Fig. 2 Comparison of Ac_3 temperatures as a function of heating rate for alloy Ck 45 and AISI 1045 with five prior microstructures, including quenched and tempered (QT), three variations of ferrite + pearlite (F+P), and ferrite + spheroidized carbide (spheroidized). The number in parentheses for the F+P microstructures indicates the volume fraction ferrite. Source: Ref 8, 9

Microalloying additions of typically 1000 parts per million or less are currently used in a variety of forged steel products to enhance properties and/or reduce production costs. Titanium, niobium, and vanadium microalloying additions have been used in medium-carbon forging steels to improve mechanical properties in the as-forged condition. As a result, these microalloyed forging steels can be economically advantageous when compared with traditional quenched and tempered (QT) grades for a variety of forged components, by reducing alloying additions (such as chromium, nickel, and molybdenum) and post-forging processing operations, especially heat treatments. Although these microalloyed steels can exhibit hardness and fatigue properties comparable to QT grades, they often have lower impact strengths than QT forgings. The lower impact properties reduce their comparative feasibility for some applications.

Microalloying additions in steels modify mechanical properties predominantly through the precipitation of carbonitrides during thermal or thermomechanical processing (TMP). These carbonitrides can be used to increase strength (through dispersive strengthening) and/or improve toughness (through microstructural refinement). Table 1 provides a summary of the austenite solubility and precipitate effects of the three major microalloying elements—vanadium, niobium, and titanium.

Because of its high solubility in austenite and the ability to precipitate on cooling, vanadium-microalloyed forging steels are preferred over those microallyed with niobium. The temperature range for forging niobium-microalloyed steels in a consistent fashion is much tighter than for the vanadium steels. In both cases, control of the cooling rate after forging is critical to ensure optimal properties.

Residuals (Copper) in Steels. With the increased use of electric furnace steel, which is made from recycled scrap, residual elements can be found in forging steels. Over the last several decades, the amount of residual copper has increased in most common forging grades, and residual copper is not eliminated in the steelmaking process. Additionally, the characteristics of the copper-iron system produce some issues for copper-iron alloys such as the lower melting point of copper (1085 °C or 1985 °F) and the low solubility of copper in iron at low temperatures.

Another issue that needs to be addressed is that copper is not soluble in iron oxide. At high temperatures, where the oxidation rate of iron is quite high, there is rejection of the copper into the metal, creating a copper-enrichment zone at the metal oxide interface. At high temperatures, the copper is liquid and can penetrate along grain boundaries with ease. This penetration debilitates the grain boundaries, which causes them to break in the presence of a tensile stress. The scenario results in a defect known as hot shortness.

Hot shortness is not a new problem; it has been known since the early 1900s when it was called red shortness. The topic arose again in the late 1950s and 1960s, when the amount of copper residuals increased in steels and the steel industry encountered production problems. Since the late 1990s the issue has once again become important, mainly for economic and environmental reasons. Hot shortness is defined as a "brittleness in metal in the hot forging range," particularly in some types of steel that contain elements with a low melting point, especially copper (Ref 10). This phenomenon occurs commonly at the surface of these steels because, during the reheating before or during forming, the content of non-oxidizing elements such as copper increases. For this reason, the term *surface hot shortness* is sometimes used. The phenomenon of hot shortness in copper-containing steels is strongly influenced by other residual elements, such as antimony, tin, and arsenic, which are more soluble in copper than in iron. Nickel also has an influence on the hot shortness of copper-containing steels, because it forms complete liquid and solid solutions with copper (Ref 11).

The oxidation of iron at temperatures in the range of 700 to 1250 °C (1290 to 2280 °F) is due to diffusion of ions through different oxide layers: hematite Fe_2O_3 (1%), magnetite Fe_3O_4 (4%), and wüstite FeO (95%) are all present. Oxidation of steel is similar to that of iron, where normally only two oxide forms are present: Fe_3O_4 and FeO. Nevertheless, noble elements such as copper do not oxidize. The solubility of copper in FeO is very low, so the copper is rejected toward the steel-oxide interface and the formation of a copper-enriched zone occurs. At the working temperatures of steel (above 1100 °C or 2012 °F), this enrichment zone is essentially pure copper and is present as a liquid phase. As a result, copper diffuses along grain boundaries into the steel, and when copper wets the grain boundaries, they become weakened. Consequently, in the

Table 1 Austenite solubility and precipitate effects for major microalloying elements

Microalloying element	Solubility in austenite	Carbonitride precipitate effects	Solute effects
Vanadium	High	Dispersion strengthening, intragranular ferrite nucleation	Solid-solution strengthening, inhibition of austenite grain growth (solute drag), recrystallization inhibition (solute drag)
Niobium	Temperature sensitive	Dispersion strengthening, austenite grain-boundary pinning, recrystallization inhibition	
Titanium	Low	Austenite grain-boundary pinning	

presence of tensile stresses the grain boundaries separate, which causes hot shortness.

Precise temperature control during the forging of steels with higher copper residuals is needed in order to avoid hot shortness problems due to residuals. Induction heating allows for a more precise control of temperature.

Forging Temperatures

The selection of forging temperatures for plain carbon and alloy steels is based on four major factors: carbon content, alloy composition, the temperature range for optimal plasticity (i.e., maximum forgeability), and the amount of reduction (Ref 12). Given these four considerations, forging temperatures are selected so that the material has the lowest possible flow stress (and therefore the lowest possible forging pressure) and maintains a temperature that prevents intergranular melting. Intergranular melting, also called burning or grain-boundary liquation, is a localized melting at the austenite grain boundaries (Ref 13). During the forging process, the sample undergoes deformational and frictional heating; if this heating, in combination with the predeformation temperature of the sample, is high enough to allow intergranular melting, then failure may occur by intergranular cracking. It is critical that the hot forging temperatures are low enough that none of the material within the sample reaches the solidus temperature, while maintaining the maximum temperature possible to minimize the flow stress, thus minimizing the required forging pressure. This maximum forge temperature, with a safety factor to account for both differences in chemistry between heats and variations in furnace temperatures, is called the maximum possible forging temperature.

When determining the recommended forging temperature, carbon content is the dominant factor. The solidus temperatures for both plain carbon and alloy steels have approximately the same linear behavior (care should be taken with steel high in silicon, which has a significantly lower solidus temperature). Recommended forging temperatures are approximately 165 °C (330°F) below the solidus temperature for plain carbon steels and an additional 30 to 55 °C (85 to 130 °F) lower for alloy steels. Above these temperatures, the steels are subject to possible damage by incipient melting or overheating (Ref 1).

Composition Ranges for Steel Alloys

Steel alloy grades are not necessarily always of the same precise composition. For example, most plain carbon and low-alloy steels can have a carbon content range of approximately 0.05 %. This variation in carbon content can produce a 90 °C (195 °F) variation in the solidus temperature for the steel. Hence, the optimal forging temperature within a single grade can vary depending on the precise chemical composition of the steel.

Steelmaking operations have improved over the years, and the steel obtained from a reputable supplier will often have a very consistent chemical composition. If there is some variation in chemistry for a given steel, induction heating of the forging billets can be used to provide a more precise control of temperature. It is important for the forger to understand the variations that can occur within steel chemistries and understand how to tune the induction heating process in order to obtain the best temperature for forging.

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Temperature Requirements for Heating Super Alloys and Stainless Steels

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Induction heating and heat treating processes are used for a range of materials and applications (Ref 1–3). These processes also apply to stainless steel and nickel-base superalloy materials and applications. These materials are processed by induction heating similar to other materials, such as plain carbon and alloy steels, but specific attributes of the materials make induction processing of them more challenging. Differences in alloy composition and the thermophysical and magnetic property interactions of stainless steels and nickel-base superalloys, as compared to plain carbon and alloy steels, impact heating efficiency, heating rates, heating uniformity, and subsequent residual stresses.

There are many applications for induction heating of stainless steel and nickel-base superalloys, including primary melting processes, heating for secondary forming, joining, heat treatment, and stress-relieving processes. The exact temperatures and control methods are specific to the alloys being processed. Alloy chemistry, prior processing, segregation, and final component microstructure considerations dictate the parameters that must be controlled during induction heating processes for these highly alloyed ferrous and nickel-base alloys.

Modeling and simulation is becoming more widely applied for component, material, and process design and optimization. Induction heating processes have also been simulated through the computational modeling of induction field interactions with components. Accurate material properties are critical to enable accurate prediction of induction processing. Critical material properties needed for prediction of induction heating include: electrical resistivity, magnetic permeability, thermal conductivity, specific heat, density, and associated coefficient of thermal expansion. Many of these properties are difficult to obtain and may be microstructure-sensitive, which is the case for electrical and magnetic properties. This article provides information regarding special consideration relative to induction heating of stainless steels and nickel-base superalloys.

Stainless Steel Alloys

There are a range of stainless steel alloys within several primary classes (Ref 4–6), each having specific final properties and unique applications. Stainless steels are generally associated with ferrous alloys, which have sufficient chromium content to enable some level of corrosion protection through the formation of a chrome oxide protective layer on the surface. The main classes of stainless steels are differentiated by the primary phase within the final component. Austenitic stainless steels are comprised primarily of face-centered cubic (fcc) austenitic crystal structure. These alloys are commonly identified by their nonmagnetic properties at room temperature. Similarly, ferritic stainless steels are comprised primarily of body-centered cubic (bcc) ferrite. These alloys are magnetic at room temperature and can be applied to a range of structural applications. Another class of stainless steels is called martensitic stainless steels. This class of alloys has the characteristic content of chromium, but also has other alloying additions that enable martensitic transformation upon heat treatment. Some alloys also contain carbon levels to enable controlled levels of carbides for added strength and wear resistance. Martensitic stainless steels are also magnetic at room temperature. Duplex stainless steels have been developed and optimized for specific combinations of properties. Similarly, precipitation-hardening stainless steels include a precipitate phase that increases the mechanical properties, such as tensile strength, after appropriate heat treatment.

Stainless steel materials are very versatile and can be used for a range of applications due to their wide range of unique properties (Ref 4, 5). Stainless steels are used for commercial products for both their exceptional corrosion resistance and their unique appearance from various surface preparation conditions, including fully polished or uniformly brushed. These materials are also applied to a wide range of industrial applications for chemical containers and transfer systems such as tanks and tubing, materials processing tooling such as rollers and cutting systems, and for elevated-temperature applications such as furnaces and energy generation systems.

Nickel-Base Superalloys

Nickel-base superalloys are alloys that are predominantly nickel with lesser amounts of other alloying constituents. These materials are categorized into a series of application and processing-based groups, including: cast and wrought (C&W); powder metallurgy (P/M); cast, heat-resistant alloys; and cast, single-crystal nickel-base superalloys (Ref 7–9). Nickel-base superalloys are applied to many high-strength and high-temperature applications, including furnace structures, high-temperature processing facilities, and gas turbines.

Nickel-base superalloys obtain their useful elevated-temperature mechanical properties and corrosion resistance primarily from solid-solution and precipitation strengthening. Some nickel-base superalloys also derive their final target properties from work hardening, but this often limits the final application temperature to below the recrystallization temperature of the alloy.

Solid-solution-strengthened nickel-base superalloys, such as Inconel 600 or Inconel 625, require solution heat treatment to achieve the desired elevated properties and corrosion resistance. Components made from these materials require an elevated solution heat treatment process followed by a controlled cooling rate to room temperature.

Precipitation-strengthened superalloys, such as IN718, require a solution heat treatment to dissolve precipitate phases, followed by a controlled cooling step to room temperature and subsequent aging. For IN718, δ phase is either partially or fully dissolved during the solution step. During subsequent cooling and aging steps, δ and γ'' are produced. Other nickel-base superalloys, such as Udimet 720, consist of γ' and γ phases. During solution heat treatment, the γ' phase is partially or fully dissolved, followed by controlled quenching to room temperature and aging to produce the optimal size and distribution of γ' precipitates.

Induction Thermal Processing of Stainless Steels and Superalloys

Induction processing of stainless steel and nickel-base superalloys is often accompanied by development of unique inductor geometries and flux orientations. Control of induction heating is directly related to the volumetric distribution and control of the flux within components made from stainless steel and superalloy materials. The applications of induction heating to stainless steel and superalloy components include: primary melting processes, preheating for primary and secondary forming processes, heat treatments, accompanying thermal processing for fusion welds, and brazing processes.

Primary Melting Processes. The chemistry of stainless steels and nickel-base superalloys dictates the need to control thermal processing to minimize oxidation and loss of costly elemental additions and introduction of contamination that will impact performance of final components. The materials are processed by numerous methods, including casting, forging, forming, and joining. The processes are often combined with heating processes to enable optimal processing. Induction heating is one of the most common processes for high-volume, clean melting (Ref 10). Vacuum induction melting (VIM) involves the application of an induction field from a coil surrounding a refractory crucible filled with the input alloy charge. The induction field couples with the charge material and provides the primary source of heating and subsequent melting. Vacuum induction melting provides the required environmental control and clean heating source to melt stainless steel and nickel-base superalloys and is used to produce large quantities of alloy ingot and mill products annually.

Induction melting enables magnetic stirring from the induced flux and resultant electromagnetic force. The use of induction fields during induction melting is used to control the overall shape of liquid metal during processing. Induction fields confine liquid metal into a controlled shape and also provide for the potential for "contactless" or "containerless" tools for continuous melt processing. An advanced dual-frequency processing technique has been investigated, in which a material such as stainless steel is melted with one frequency and the melt shape or confinement is controlled by a coil with another frequency (Ref 11). This approach is unique and could enable efficient, advanced containerless final forming of mill products from a continuous casting process.

Preheating for Primary and Secondary Forming Processes. In addition to primary melting processes, induction processing is used for a range of secondary forging and forming processes. Induction heating of stainless steel billets or rods in the form of multiples (mults) is very efficient with automated transfer or walking-beam processing methods. Induction heating of forging stock (billet or rod material) enables rapid heating and minimization of time at temperature. Extended time at temperature from a box furnace results in heavy scale formation, loss of alloy to the scaling process, and excessive grain growth. Because stainless steels contain chromium and often reasonable amounts of nickel, these materials are expensive compared to plain carbon and alloy steels, so minimization of scaling and alloy loss provides a direct economic benefit. Induction heating of forging stock also provides limited exposure time at elevated temperature, which enables control of grain size in the preheated stock and can significantly impact forging process success and final component microstructure and properties.

Induction preheating of 316 stainless steel stock prior to extrusion has been done successfully. Studies of preheating optimization were accomplished by computational modeling and simulation of the entire sequence of heating and deformation processes (Ref 12). The work shows that the force-displacement profile results from the extrusion simulations are very comparable with those of experimental measurements. Including the simulated thermal gradients from the specific induction heating process provides for increased accuracy of steady-state force after the initial breakthrough force drop as compared to assuming a completely uniform temperature profile in the workpiece.

Other computational modeling efforts apply to the bulk heating of stainless steel for secondary processing. The ability to uniformly heat bulk stainless steel workpieces is very difficult. There are applications of induction heating of stainless steel to a semi-solid heated state for thixotropic-type processing (Ref 13). The thermal processing of material for thixotropic processing is extremely critical to enable proper temperature uniformity, and proper and consistent volume fractions of solid and liquid. The computational simulation approach for 310 stainless steel slugs is shown to be possible and enables development and optimization of the required induction heating parameters to achieve the desired thermal history and profile.

Induction heating applies to many preheating processes other than bulk heating for forging and large plastic deformation. Induction heating is also applied to heating sheet and strips of stainless steel to enable elevated-temperature forming. The method of induction heating sheets and strip impacts heating rates, uniformity, and efficiency. There are methods of applying induction fields both longitudinal and transverse to sheet directions (Ref 14). Optimal induction field direction is different for different heating conditions and target temperatures. Due to the low magnetic permeability of stainless steels and the related impact on induction heating of sheet and strip by conventional longitudinal flux orientations, optimized coil designs for transverse heating of stainless steel sheets are designed and applied to optimize heating uniformity and efficiency (Ref 15).

The use of induction heating of stainless steel strip results in rapid heating of the material for various subsequent processing steps. Efforts have been conducted to study the ability to rapidly heat stainless steel strip by transverse flux induction heating (Ref 16). Heating rates up to 1000 °C/s (1830 °F/s) are achieved for stainless steel strip. Studies show that if various grades of stainless steel are heated to specific recrystallization temperatures, complete recrystallization is achieved with no dwell time required. Optimization of this process requires study of recrystallization kinetics for each specific alloy. The results from the previous work show that reduced recrystallized grain sizes are achieved through the rapid thermal processing while maintaining comparable mechanical properties to those of conventional industrial processed material.

Heat Treatments. Induction heating is applied to stainless steels and nickel-base superalloys for bulk and surface treating processes for final components. Many of the standard heat treating processes using traditional batch or continuous furnaces are accomplished by induction heating of individual components (Ref 17, 18). The heat treatment processes for stainless steels depend on the specific alloy; Table 1 lists some induction heating processes and parameters for several stainless steels.

Martensitic stainless steels are readily heated to the austenitizing temperature by induction heating. Subsequent quenching produces martensite within the processed material and produces increased mechanical properties. An effort on stainless steel shafts was reported where induction austenitizing and quenching was applied to achieve the desired microstructure and properties (Ref 19). Induction heating is rapid and effective for bulk heat treating small-cross-section components and provides robust and repeatable results. In the reported example, the hardness of the shaft was doubled by the applied heat treatment.

Fusion welding of martensitic stainless steels is complicated. The various thermal histories in the fusion and heat-affected zones result in a range of microstructure evolution from as-quenched martensite to overtempered base material. Induction heating is applied to preheat weld material to slow the cooling

Table 1 Typical induction heat treatments and processing parameters for select stainless steels

AISI alloy name	Annealing				Hardening				Tempering			
	Temp, °C	Temp, °F	Coolant	Hardness, Brinell	Temp, °C	Temp, °F	Coolant	Hardness, R_c	Temp, °C	Temp, °F	Coolant	Hardness, R_b/R_c
302	1066–1149	1950–2100	Water	150	Nonhardenable				Nonhardenable			
304	1066–1149	1950–2100	Water	150	Nonhardenable				Nonhardenable			
316	1066–1149	1950–2100	Water	150	Nonhardenable				Nonhardenable			
321	1010–1149	1850–2100	Water	160	Nonhardenable				Nonhardenable			
347	1066–1149	1950–2100	Water	160	Nonhardenable				Nonhardenable			
410	Generally furnace annealed				1010–1066	1850–1950	Oil or air	~43	204–649	400–1200	Air	R_b 97–R_c 41
420	Generally furnace annealed				1038–1066	1900–1950	Oil or air	~54	177–510	350–950	Air	R_c 48–52
430	788–843	1450–1550	Air	150–180	Generally not hardened				Generally not hardened			
440A	Generally furnace annealed				1038–1121	1900–2050	Oil or air	56–57	177–510	350–950	Air	R_c 50–57
440B	Generally furnace annealed				1038–1121	1900–2050	Oil or air	58–59	177–510	350–950	Air	R_c 54–59
440C	Generally furnace annealed				1038–1121	1900–2050	Oil or air	59–60	177–510	350–950	Oil or air	R_c 55–60

Adapted from Ref 17

process after welding, or as a means of heating the base material and weld materials immediately after the welding process to control the transformation products to optimize the resultant mechanical properties. Studies on 410 stainless steel show that postweld induction thermal processing increases the ductility, toughness, and strain-to-failure for final manufactured components (Ref 20). In-process thermal processing is a time-effective cost and manufacturing approach to achieve the desired final properties in complex materials and components. Using high-strength stainless steel materials for fabrications is one approach for reducing the weight of systems, such as in future automotive structures.

Bulk heat treatment of nickel-base superalloys is also performed by induction heating methods. Similar to stainless steels, there are many types of heat treatment processes for nickel-base superalloys. An interesting study on the aging of superalloy IN738LC showed an appreciable benefit from induction aging (Ref 21). The study compared the aging kinetics of solution heated and quenched samples of IN738LC by three methods: conventional furnace heating and aging, salt bath heating and aging, and induction heating and aging. This work demonstrates that the induction heating and aging process results in a much greater rate of γ' nucleation during the initial two minutes of rapid heating and aging as compared to the other processes, even though the rate of heating between the induction heating and salt bath processes is noted to be equivalent. It was proposed that the electromagnetic force from the induction field resulted in increased diffusivity and hence increased nucleation and growth of the γ'precipitate particles. The induction heating process was also noted to show what appears to be an increased rate of overaging at increased times at high exposure temperature as compared to the salt bath processed material. The finding that induction processing has an impact on the kinetics of precipitate nucleation and growth may be extremely useful for local processing of nickel-base superalloys, or for development of rapid, cost-effective thermal processing methods for components. It is of interest to study the claimed results further to ensure the proposed source of aging enhancement is truly a result of electromagnetic-field-enhanced diffusivity as opposed to greater heating efficiency from internal induction heating as compared to surface heating processes, such as salt bath heating.

Local heat treatment of steel materials is commonplace for alloy steels and for many types of stainless steels. The application of surface or local thermal processing of nickel-base superalloys is less common but has been successfully accomplished to produce unique properties for aerospace components and is being further developed. An effort was conducted to develop and demonstrate local heat treatment of alloy 718 material (Ref 22). This effort resulted in successful computational simulation of induction heating of alloy 718 material. It was shown that computational modeling can be combined with induction process controls to enable tailoring of the thermal processing and profiles within components to achieve the target microstructure and properties within local volumes of superalloy components. A commercial finite-element modeling code was used for the simulation of the induction heating process. This effort was reported as providing successful results and could lead to increased tailoring of superalloy microstructures on a local basis within a final component.

Other superalloy materials and components have been locally thermal processed by induction heating. A process has been developed and patented (Ref 23) that locally heats the rim region of nickel-base superalloy turbine engine rotors to produce local grain growth and optimized local properties (Ref 24). The induction process used to locally heat treat nickel-base superalloys includes both optimized heating coils and integral cooling methods, which is similar to other more conventional heat treating processes for surface hardening of steel. Like steel surface hardening, this unique process for nickel-base superalloy rotors is aimed at changing the local microstructure to enable optimized local properties. The temperatures within turbine engines are very high and are being further increased to improve engine efficiency, but this is greatly taxing the capabilities of components with uniform microstructures, so local optimization is required. Induction heating the rim of nickel-base rotor rim regions results in increased grain size and an associated increase in creep capabilities, while the bore region is optimized for increased tensile and fatigue strength. Figure 1 shows a schematic of the local induction heating process for nickel-base superalloy rotors.

Induction surface treating is commonly performed for a range of materials to increase local properties, such as a hardness and strength in alloy steels (Ref 2). These types of processes are also used for stainless steel materials. There are also unique applications of surface treatment of stainless steels. An effort was reported in which metastable austenitic stainless steel material was used for an application where increased strength was needed from cold working and transformation of the austenitic structure to martensite, but where this structure was susceptible to environmental attack (Ref 25). A unique process was devised to produce the required martensitic structure throughout the volume of the material and then a high-frequency induction heating process that localizes the heating to the very near surface was applied to solution the martensite and to stabilize a complete austenitic structure on the very surface of the component. This unique application of induction heating resulted in utilization of a lower-cost stainless steel grade, capturing the advantage of increased strength from deformation and martensitic transformation, and subsequently recovery of the surface environmental-resistance capabilities. This is an excellent example of the flexibility of induction heating.

Thermal Processing for Fusion Welds. Induction heating is also applied to a range of materials for manipulation of residual stresses. In some cases, induction heating is applied to reduce the residual stress from prior forming or welding processes, but in some applications, induction heating is a preferred approach to introduce bulk residual stresses into components. In the nuclear power industry, stainless steel tubing is widely used for its typical corrosion resistance. When tubes are fusion welded, large residual stresses are produced that are nonoptimal from a stress-corrosion cracking (SCC)

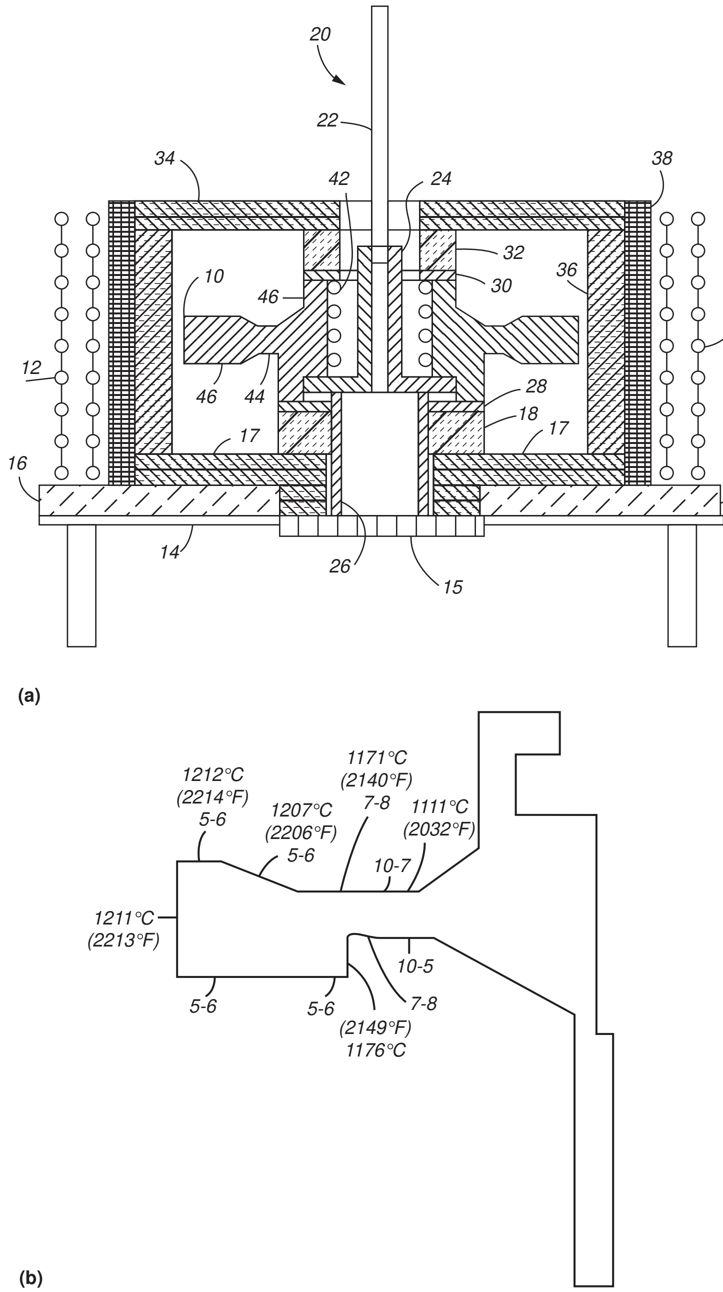

Fig. 1 Schematic of the induction heat treatment process for locally heat treating the rim region of nickel-base rotors used in turbine engines, where (a) shows the induction coils (40), graphite susceptors (36), and cooling fixtures (42), and (b) shows an example nickel base rotor with local temperature and grain size (ASTM grain size number) measurements noted. Source: Ref 23

standpoint. Induction heating is applied to stainless steel tubing to produce beneficial inner diameter surface compressive stresses in the tubing that is in contact with reactor water environments (Ref 26–28). The developed compressive residual stress mitigates the formation of SCC. Careful measurement of residual stresses in as-welded tubing shows that the residual stress on the inner surface is tensile in nature but completely compressive after optimal induction heat treatment. Optimal induction heat treatment provides compressive residual stresses on the inner surface that result in a 15× improvement in intergranular SCC (IGSCC) as compared to untreated tubing (Ref 27).

Thermal Processing for Brazing Processes. Induction heating is also applied to brazing processes, where clean, local heating is needed to melt braze alloys and to enable wetting to the base components to be joined. Induction brazing processes require understanding of the thermal history of the base materials and braze alloy during the entire brazing process. Cutting tools are brazed to high-strength, high-toughness stainless steels by induction heating methods. These methods need to be controlled to ensure the thermal cycle does not adversely affect the base materials. In one example tungsten carbide material was induction brazed to 420 martensitic stainless steel (Ref 11). The occurrence of soft spots in the stainless steel was observed and investigated. During the original induction brazing process, the temperature of the 420 stainless steel was allowed to reach very high temperatures where detrimental microstructure changes occurred. At temperatures above 500 °C (930 °F) carbides started to precipitate to a maximum rate at 650 °C (1200 °F). At 700 °C (1290 °F) grain growth was observed. These changes in the microstructure are associated with decreased strength and hardness. For this application, a careful analysis of the induction heating process and thermal history was performed. The application of an optimized induction coil along with a copper cooled brazing fixture resulted in establishing an enhanced thermal profile that mitigated the microstructure changes in the 420 stainless steel and eliminated the problems of soft spots in the final components. This shows the importance of understanding and controlling the thermal conditions during induction brazing and heat treatment processes.

Brazing processes are very flexible; they enable joining different materials. Induction heating methods are useful in providing the required heating that is optimal for the base metals and the brazing alloy. A process was reported for the vacuum induction brazing of titanium to Inconel alloy components (Ref 29). Optimization of braze alloy and the thermal cycle resulted in successful joining of these and other dissimilar metals.

Computational Modeling of Induction Heating Processes

Computational modeling and simulation apply to many material and component processing methods (Ref 30, 31). The computational tools and methods allow for assessment of processing parameters based on prediction of results for specific materials and component configurations. Induction heating methods are simulated for the two main processing applications: complete heating of material for bulk thermal processing and surface heating for local thermal processing and local manipulation of microstructure and properties (Ref 32, 33).

The complexity of induction heating processes requires a means of simulation of the process to ensure optimal thermal processing. Coil design, including coil windings, geometry, location relative to the component, flux concentrators, and electrical power input all make a significant impact on the coupling of the flux and subsequent joule heating of the material.

Computational modeling applies to a range of stainless steel and nickel-base superalloys (Ref 12, 13, 22, 28, 34). Efforts are focused on simulation of heating effects of induction