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Have you ever wondered how metal properties are being changed? You must have heard of heat treatment. In fact, in today’s industrial world, there are clear differences between good products and highly exceptional ones, which lie with the very structure of the metals used. It is a must for all engineers, manufacturers, and material scientists to have understanding and deep knowledge of heat treatment of metals. They must understand it isn’t merely about making the metal harder but about how they can precisely change its properties to meet specific application requirements. From enhancing its durability and strength to improving wear resistance and extending the component lifespan. Stay with me as i uncover and help you deal with material fatigue, cut production cost and introduce some innovative material capabilities. This content is designed to equip you with the practical knowledge and advanced strategy you need as an engineer. Before the end of this reading, you’ll be able to transform raw materials into high-performance pieces that will stand the test of time. Let’s begin! You should learn How to Heat Treat Aluminum & Aluminum Alloy with this detailed guide! What is the Heat Treatment of Metal? Heat treatment is a crucial process for obtaining desired properties in metals. Various methods are used to heat and cool metals, ensuring their specific properties. Metallurgists continuously improve the outcomes and cost-efficiency of these processes by developing new schedules or cycles. These methods produce metals of various standards with unique physical and chemical properties. It is a controlled process that changes the microstructure of metals and alloys like steel and aluminum to impart properties that improve a component’s working life, such as increased surface hardness, temperature resistance, ductility, and strength. When attempting to change the properties of metals, the first factor to consider is heat treatment. This mechanical process involves heating metal at a specific temperature with a standard cooling method to obtain the desired properties. Heat treatment is the process of heating metal without letting it reach its molten, or melting, stage and then cooling it in a controlled manner to get the desired mechanical properties. Heat treatment is used to either make metal stronger or more malleable, more resistant to abrasion, or more ductile. In the engineering field, heat treatment is a metalworking process that involves changing a material’s physical and sometimes chemical properties. It is also said to be a way in which the physical or mechanical properties of a metal are changed by heating and cooling methods without changing the shape of the working metal. You should also learn about Annealing with this detailed guide! Theory of Heat Treatment Heat treatment can differ depending on the metal material, but there are three main differences in the process: the heating temperatures, the cooling rates, and the quenching types. Tweaking this process will get you the properties you desire. Well, heat treatments are often performed on metals containing iron, which are known as ferrous metals. Annealing, hardening, normalizing, and tempering are done on such kinds of metals. Proper heat-treating equipment will be required so one can accurately control the factors around heating, cooling, and quenching. For instance, the furnace must be the proper size and type to control temperature, including the gas mixture in the heating chamber, and you need the appropriate quenching media to cool metal correctly. Purpose of Heat Treatment The following are the purposes of heat-treating metals: To improve ductility and toughness Increase the wear and corrosion resistance of a metal. Improve electrical and mechanical properties. Homogenize the structure to remove coring. Spheroidize tiny particles. Improve machinability and toughness. Grain size refinement. Relieving internal stresses. The Three Stages of Heat Treatment Heat treatment serves several purposes when it comes to metal, and these can be achieved in three stages. These three stages of heat treatment include heating, soaking, and cooling. 1. Heating Heating is the first stage in a heat-treating process. It is done to change the structure of alloys when heated to a specific temperature. The alloy is said to be at room temperature either as a solid solution, a mechanical mixture, or a combination of both. During this phase, the metal is gradually heated to a specific temperature to alter its internal microstructure and prepare it for quenching, annealing, tempering, or other processes. The key purpose of the heating phase is to soften or harden the metal, relieve internal stresses, refine grain structure, and prepare the metal for further mechanical or thermal treatment. Some important heating guidelines you should know are: Heating Rate: Should be slow and uniform to avoid thermal shock or distortion. Soaking Time: Once the desired temperature is reached, the metal is held (soaked) for a specific time to ensure uniform temperature and microstructural changes. Atmosphere Control: Protective gases may be used to prevent oxidation or decarburization during heating. Finally, the heating phase is fundamental in heat treatment, as it determines how the metal’s internal structure transforms. The exact temperature and time depend on the type of metal, desired outcome, and specific treatment process. The proper control of heating is important to achieve optimal mechanical properties without introducing defects. 2. Soaking The soaking phase is the second crucial step in the heat treatment process, following the heating phase. Once the metal reaches the desired temperature, it is held at that temperature for a specific period, which is known as soaking or holding time. Soaking is the stage at which the complete part of the heated metal completely changes its structure. The mass of the metal will determine the time it will be soaked. In other words, soaking is when a part of metal evenly turns red due to being subjected to heat for some time. The purpose of this phase is to allow uniform heat penetration throughout the entire part, ensure complete microstructural transformation, allow dissolution or redistribution of alloying elements, and finally to eliminate internal stresses and homogenize grain structure. It will take small parts at least 15–30 minutes to be fully soaked, medium parts take 30–60 minutes, while large or thick parts take 1–2 hours or more. But the general rule of thumb is 1 hour per inch of thickness. Take note of that! You should be aware that over-soaking can lead to grain growth, reducing strength and toughness. whilst, under-soaking results in incomplete transformation, leading to poor mechanical properties. This is to say uniform temperature must be maintained throughout the soaking period. The soaking phase is essential for achieving uniform metallurgical changes throughout the metal. By holding the metal at a specific temperature for a calculated time, internal structures can realign, dissolve, or transform as needed. Precision in both time and temperature is crucial for the success of the entire heat treatment process. You should learn about Metals with this detailed guide! 3. Cooling The cooling phase is the final stage of the heat treatment process. After the metal has been heated and soaked at the desired temperature, it is cooled in a controlled manner to achieve specific mechanical and structural properties. There are different ways of achieving this depending on the desired outcome. The rate and method of cooling directly influence the final hardness, strength, ductility, grain structure, and other characteristics of the metal. The purpose of this cooling phase is to lock in microstructural changes formed during heating and soaking, achieve desired mechanical properties like hardness or toughness, avoid internal stresses, distortion, or cracking, and determine whether the metal will be hard, soft, or tough. Cooling Rate Impact on Microstructure: Cooling Rate Microstructure Formed Resulting Properties Fast (quenching) Martensite Very hard but brittle Medium (air) Pearlite/Bainite Balanced strength and toughness Slow (furnace) Ferrite + Pearlite Soft, ductile, and machinable Types of Cooling Methods 1. Quenching: This is a fast way of cooling the metal, and the common mediums used are water, brine, or oil. The purpose is to increase hardness and strength (e.g., in steels) by transforming austenite into martensite. This is why it is used in hardening processes for high-carbon steels. However, cracking or warping might occur if not controlled. 2. Air Cooling: is a moderate cooling rate or method that uses the medium of still or forced air. It is used for normalizing and annealing to relieve stress while maintaining decent hardness. Structural steel and stainless steel are some metal materials that undergo these cooling methods. 3. Furnace Cooling: This cooling is a common slow cooling that is also called annealing or controlled cooling. Its purpose is to produce soft, ductile, and stress-free metals by cooling very slowly in the furnace. It is often used for Low carbon steels, aluminum alloys, and copper. 4. Quenching + Tempering: This is a controlled reheating after cooling method performed to harden the metal (through quenching) and then reduce brittleness (through tempering). It is commonly done for tool steels, spring steels, and crankshafts. Some considerations you must follow during the cooling phase are the material type (e.g., carbon steel, aluminum), the desired mechanical properties, the risk of warping/cracking and the size and shape of the part. The cooling phase is just as important as heating and soaking. The method and speed of cooling determine whether the metal ends up hard and brittle, soft and ductile, or somewhere in between. Choosing the right cooling process is essential to tailor the material’s final characteristics for its intended application. Proper control during this phase ensures the desired balance between strength, flexibility, and durability. How is Heat Treatment Done? Heat treatment is a process that involves heating metal, holding it at a specific temperature, and then cooling it back. This process alters the metal’s mechanical properties due to the high temperature, which affects its microstructure. The outcome depends on factors such as the time of heating, the temperature of the metal part, the rate of cooling, and surrounding conditions. The properties of the metal, such as electrical resistance, magnetism, hardness, toughness, ductility, brittleness, and corrosion resistance, change during heat treatment. An alloy may exist in three different states during heat treatment: a mechanical mixture, a solid solution, or a combination of both. The holding stage, or soaking stage, keeps the metal at the desired temperature, with the duration depending on the requirements. The holding time depends on the material type and part size. After the soaking stage, the metal must be cooled in a prescribed manner, causing structural changes. Different media, such as brine, water, oil, or forced air, control the rate of cooling. Brine absorbs heat fastest, while air is the slowest. Furnaces can also be used in the cooling process for high precision when slow cooling is necessary. You should learn about Malleability with this detailed guide! Methods of Heat Treating Metals Common heat-treating methods include annealing, hardening, quenching, and stress-relieving. Each method has a unique process to produce specific results. Annealing Annealing heat treatment is used to alter the microstructure of a metal. This enhances its ductility while reducing internal stress and overall hardness. This makes the shaping process of the material easy, preventing it from cracking. Annealing has to do with heating metal to a point where the crystalline structure becomes fluid while the metal remains solid. This temperature is maintained for the metal so that any flaws in the material can heal themselves. After that, the metal is gradually allowed to return to room temperature to form a more ductile crystalline structure. Annealing is a process used to soften metal, increase ductility, and improve machinability. In the process, metal is heated to a high temperature (just below melting point), held, and then cooled slowly in the furnace. This helps to refine grain structure, remove internal stresses, and restore ductility. It is used for sheet metal, wire, and parts that need further shaping or forming. Annealing Temperature Range for Softening Metals: Metal Type Temperature Range Low Carbon Steel 870°C–910°C (1600–1670°F) Stainless Steel 1040°C–1120°C (1900–2050°F) Aluminum Alloys 345°C – 415°C (650–780°F) Copper Alloys 425°C–650°C (800–1200°F) When performing annealing on steel, the soaking temperature should be from 870°C to 910°C (1600–1670°F). The Soaking time should be 1 hour per inch of thickness to ensure full softening and stress relief. Hardening Hardening is a heat treatment process for enhancing a surface metal’s hardness by heating and rapid cooling. It has to do with heating the material in a hardening furnace to a point that transforms its internal structure without melting it. Next, we hold the metal at the temperature for one hour per inch of thickness, followed by rapid cooling. There’s a harder and more stable crystalline structure because of the rapid cooling. Hardening increases a metal’s hardness and strength by heating followed by rapid cooling (usually via quenching). During the process, steel is heated above its critical temperature, hold to form austenite, then quenched to trap carbon and form martensite. This is done to enhance wear resistance and load-bearing capacity. This is why the metal use in materials with durability like cutting tools, dies, and automotive and industrial parts. Hardening Temperature For Metal Types: Metal Type Temperature Range Medium/High Carbon Steel 760°C – 900°C (1400–1650°F) Tool Steel 900°C–1200°C (1650–2200°F) When hardening steel, the soaking temperature should be between 760°C and 900°C (1400–1650°F). The soaking time should be shorter than annealing, which is enough to allow austenitization without excessive grain growth You should also learn about the 26 Different Types of Furnaces and Their Uses with this detailed guide! Quenching Quenching heat treatment is a process of rapidly cooling the metal to get the physical or mechanical properties needed. Most commonly, people use oil to cool the heated material. However, water, brine, and air can be used based on the material and the qualities you want. The quenching heat-treating process sets it apart from others because the metal is heated to a point below the melting point at which the crystalline structure is fluid. The properties you want will determine the period they will be held for. Afterward, it is quenched in one of the media to reduce the temperature of the material and yield the necessary internal structure. Just as explained earlier, quenching is the rapid cooling of a metal, usually after heating to a high temperature, to harden the material. The process is achieved by heating the metal to its austenitizing temperature and then rapidly cooling it in water, oil, or air. Its purpose is to increase hardness but also make the material brittle and it is used for high-strength tools, blades, and hardened steel parts. Stress Relieving This process has to do with heating the material above the point where the internal structure transforms and then air-cooling it at a particular rate. It allows for a more stable structure, reducing internal stress and enhancing the strength and hardness of the metal. It is particularly useful for metals that have been subjected to stress-inducing forming processes, such as machining, straightening, and rolling. To further explain, stress relieving is a heat treatment used to reduce internal residual stresses in metal without altering its structure drastically. The method helps to improve dimensional stability and reduces the risk of warping or cracking. It is used for welded structures, castings, and machined components. During the process, the metal is heated to a moderate temperature (typically 550°C – 700°C / 1020°F – 1290°F), held, and then cooled slowly. Aging Precipitation hardening or aging, is a heat treatment method used to increase the yield strength of malleable metals by producing uniformly dispersed particles within the grain structure. This process, which occurs after another heat treatment, reaches medium temperatures. Aging, also known as precipitation hardening, is a process used to increase the strength of alloys, especially aluminum and stainless steel. The process is performed after solution treatment and quenching; then the metal is heated to a lower temperature (120°C – 190°C / 250°F – 375°F) and held for hours. The various types of aging you should know are Natural Aging which occurs at room temperature, and Artificial Aging which is carried out in an oven. It is used for aerospace parts, high-strength aluminum components, Carburization The metal undergoes heat treatment in the presence of an element that dissolves to produce carbon. The metal’s surface absorbs the carbon that has been released. The surface becomes harder than the inner core due to an increase in carbon concentration. Carburization is a surface hardening process where carbon is diffused into the surface of low-carbon steel. During its process, the steel is heated (around 900°C – 950°C / 1650°F – 1750°F) in a carbon-rich environment (gas, solid, or liquid). It helps to produce a hard, wear-resistant surface while maintaining a tough, ductile core. This is why it is used in automobile industries for materials like gears, cams, crankshafts, and other parts subjected to surface wear. Tempering Tempering reduces excess hardness and brittleness during hardening, relieves internal stresses, and makes metals suitable for various applications. Temperatures are typically lower than hardening temperatures, with higher temperatures resulting in softer final workpieces. Cooling rate doesn’t affect structure. It is a heat treatment process applied to hardened steel or iron to reduce brittleness and increase toughness. Tempering helps to soften the metal slightly to relieve internal stresses caused by hardening and is often used for tools, springs, and components requiring a balance of strength and flexibility. During the process, heat the metal to a temperature below its critical point (150°C – 650°C / 300°F – 1200°F), then cool it in air. The table below will help you have more understanding of the various methods of metal heat treatment: Process Purpose Cooling Method Typical Temp Range Tempering Reduce brittleness, increase toughness Air cooling 150°C – 650°C (300°F – 1200°F) Carburization Surface hardening via carbon diffusion Quench after heating 900°C – 950°C (1650°F – 1750°F) Aging Strengthen alloys via precipitates Air cooling 120°C – 190°C (250°F – 375°F) Stress Relieving Reduce internal stress Slow air or furnace 550°C – 700°C (1020°F – 1290°F) Quenching Trap hard structure (martensite) Water, oil, or air Depends on material Hardening Increase hardness and strength Quenching 760°C – 900°C (1400°F – 1650°F) Annealing Soften, improve ductility Very slow (furnace) 500°C – 950°C (930°F – 1740°F) Applications and Industry Impact of Heat Treatment Various industries today rely on heat treatment, as it is an essential process across numerous high-performance and safety-critical industries. Its ability to enhance the strength, durability, corrosion resistance, and machinability of metals makes it useful in industries like 1. Automotive Industry – It ensures wear resistance and longevity of components exposed to high friction and load. This is why components like gears, crankshafts, camshafts, and valve springs are heat-treated for optimal durability and fatigue resistance. 2. Aerospace Industry – the aircraft demand materials that are both lightweight and strong. Heat-treated aluminum and titanium alloys meet this need. Components like turbine blades, landing gear components, and fasteners are heat-treated to withstand extreme stress and temperature. 3. Tool & Die Industry – cutting tools, dies, and molds require exceptional hardness and wear resistance. This is why Heat treatment is critical for drill bits, injection molds, punches, and saw blades to perform precisely over long periods. 4. Medical Field – Heat treatment is perform on surgical instruments to be corrosion-resistant, biocompatible, and hard enough to cut or hold shape. Heat-treated scalpels, orthopedic implants, and dental tools ensure longevity and precision in critical applications. 5. Energy and Power Generation – heat-treated components are used in turbines, boilers, and nuclear reactors where creep resistance and thermal stability are crucial. For example, turbine shafts and pressure vessels are treated to withstand fluctuating loads and temperatures. 6. Defense and Military – parts like armor plates, weapon parts, and projectile casings are heat-treated to deliver strength under impact and prolonged use. 7. Construction and Heavy Equipment – structural steel, bolts, and bearings are heat-treated to improve load-bearing capability and impact resistance, especially in cranes, bulldozers, and bridges. Specific Component Examples and Why Heat Treatment Matters The table below shows different industrial components and why heat treatment must be perform: Component Why Heat Treatment is Important Gears To increase surface hardness and reduce wear in high-friction environments Shafts To enhance tensile strength and prevent bending or fatigue under heavy loads Turbine Blades Must resist creep, oxidation, and high-temperature deformation Surgical Instruments Need to be sterilizable, corrosion-resistant, and maintain sharp edges Drill Bits Require hardness and edge retention for cutting through tough materials Springs (Valve or Suspension) Need tempering to balance flexibility and strength Bearings Undergo case hardening to provide a tough core and hard surface for longevity Learn about Blast Furnaces with this detailed guide! Benefits of Heat-Treated Components Heat treatment is not just a technical process; it’s a necessity across industries. From the engine in your car to the turbine in a jet, from surgical tools to the drill bit in your toolbox, heat-treated metals drive efficiency, durability, and safety. Its real-world impact is visible in the performance and resilience of the products we rely on every day. Enhanced performance and reliability in harsh operating environments Longer lifespan, reducing maintenance and replacement costs Precision and dimensional stability, especially in tooling and aerospace Optimal strength-to-weight ratios, critical in vehicles and aircraft Consistency and safety in medical and defense equipment Future Trends and Innovations in Heat Treatment As industries evolve, so does the technology behind heat treatment. Innovations are being driven by demands for precision, energy efficiency, sustainability, and digital transformation. Below are the key trends shaping the future of heat treatment in metals and alloys: Advanced Heat Treatment Processes 1. Plasma Nitriding – is a low-temperature surface hardening process that introduces nitrogen ions using a plasma field. It helps to produce parts with extremely hard, wear-resistant surfaces with minimal distortion. This is why it is ideal for precision tools, molds, and medical implants. 2. Laser Heat Treatment – it uses a high-energy laser beam to selectively harden specific areas of a component and it enables localized treatment, preserving the properties of surrounding areas. Laser heat treatment is high precision, minimal distortion, and has no need for quenching. 3. Cryogenic Treatment – involves cooling materials to sub-zero temperatures (as low as −190°C or −310°F) using liquid nitrogen. It refines grain structure, relieves internal stress, and improves wear resistance and dimensional stability, and it is common in tooling, aerospace parts, and high-performance motorsports. Sustainability in Heat Treatment 1. Energy-Efficient Furnaces – modern furnaces now include better insulation, regenerative burners, and waste heat recovery systems, reducing energy consumption by up to 40%. 2. Induction Heating – It now uses electromagnetic fields to heat metal only where needed, with high efficiency and minimal heat loss. It also help with faster heating times and reduced CO_2 emissions compared to traditional methods. 3. Eco-Friendly Atmospheres – The use of cleaner gases (e.g., nitrogen, hydrogen mixtures) to replace toxic or high-carbon emissions atmospheres in processes like carburizing. 4. Reduced Carbon Footprint – The integration of solar power, electric-powered furnaces, and smart energy management systems is becoming a priority. Industry 4.0: Smart Heat Treatment 1. Sensor Integration & IoT – This help with real-time monitoring of temperature, pressure, cycle time, and atmosphere using embedded sensors. It also improves process control, safety, and repeatability. 2. Artificial Intelligence (AI) & Machine Learning – The AI models analyze heat treatment data to predict failures, suggest process adjustments, and even optimize treatment cycles automatically. It helps reduce human error and ensures consistency in quality. 3. Digital Twins – This is a virtual replica of the heat treatment process that allows for simulation, testing, and optimization before real-world application. It help reduces trial-and-error, saves time, and enhances R&D capabilities. 4. Predictive Maintenance – With machine learning algorithms using sensor data to predict furnace component failures (like burners or insulation breakdown) before they happen. This help minimizes downtime and lowers maintenance costs. The future of heat treatment lies in precision, intelligence, and sustainability. With technologies like plasma nitriding, laser treatment, and cryo-processing, manufacturers can enhance material performance with pinpoint accuracy. Also, green technologies and energy-efficient systems are reducing the environmental impact. Coupled with AI, IoT, and predictive analytics, heat treatment is stepping into the Industry 4.0 era, transforming from a traditional process to a smart, responsive, and optimized system. These innovations promise a safer, cleaner, and more cost-effective future across all industries relying on treated metals. Conclusion: Heat Treatment of Metals Heat treatment is a foundational process in metallurgy that transforms the physical and mechanical properties of metals to meet specific performance demands. Through its three main phases, heating, soaking, and cooling, heat treatment enables improvements in hardness, strength, ductility, toughness, and wear resistance. Processes like annealing, quenching, hardening, tempering, carburization, aging, and stress relieving play vital roles in shaping metals for diverse industrial applications. From automotive gears and aerospace turbine blades to surgical tools and heavy-duty machinery, heat-treated metals are critical to modern engineering. As industries move toward precision, sustainability, and digital integration, innovations such as plasma nitriding, laser heat treatment, cryogenic processing, and smart technologies (AI, sensors, digital twins) are revolutionizing how heat treatment is applied. With increasing emphasis on efficiency and environmental responsibility, heat treatment remains a cornerstone of both traditional manufacturing and cutting-edge industrial design. FAQs What is heat treatment in metallurgy? Heat treatment is a controlled process of heating and cooling metals to alter their physical and mechanical properties without changing their shape. What are the three main phases of heat treatment? Heating phase – metal is raised to a specific temperature Soaking phase – metal is held at that temperature to allow structural changes Cooling phase – metal is cooled at a controlled rate to achieve desired properties What are the most common types of heat treatment? Annealing – softens the metal Quenching – hardens by rapid cooling Tempering – reduces brittleness after quenching Hardening – increases strength and wear resistance Carburization – adds carbon to the surface Aging – strengthens alloys Stress Relieving – reduces internal stresses Which industries depend heavily on heat-treated metals? Automotive, aerospace, medical, defense, tool & die, construction, and energy sectors all rely on heat-treated components for strength, safety, and performance. What are some components that require heat treatment? Gears, shafts, springs (automotive) Turbine blades, fasteners (aerospace) Surgical instruments (medical) Drill bits, molds, cutting tools (manufacturing) How is the heat treatment process evolving? New technologies like plasma nitriding, laser heat treatment, cryogenic treatment, and AI-powered control systems are improving precision, speed, and sustainability. Is heat treatment environmentally sustainable? Yes. With modern energy-efficient furnaces, clean atmospheres, and waste heat recovery systems, heat treatment is becoming more eco-friendly. Can all metals be heat treated? No. Most ferrous metals (steel, iron) are heat treatable. Some non-ferrous metals like aluminum, titanium, and certain copper alloys can also be treated, depending on their composition. References and Resources for Further Reading Books & Textbooks Heat Treatment, Selection, and Application of Tool Steels Author: William E. Bryson Publisher: Hanser Gardner A practical guide focusing on tool steels, hardening, and tempering. Metallurgy for the Non-Metallurgist Author: Harry Chandler Publisher: ASM International Excellent beginner-friendly resource on metals and heat treatment. Heat Treatment of Metals Author: B. Zakharov Covers basics to advanced heat treatment principles. Principles of Heat Treatment of Steel Author: George Krauss A foundational textbook detailing the theory and practice of steel heat treatment. Metals Handbook: Heat Treating (Vol. 4) Publisher: ASM International An in-depth, comprehensive resource on all known heat treatment processes, materials, and equipment. Online Articles & Databases ASM International – asminternational.org The most authoritative source for materials science and heat treatment standards, data sheets, and innovations. MatWeb – matweb.com Material property database where you can look up heat treatment details for various metals and alloys. Thermo-Calc Software White Papers – thermocalc.com Technical documents on simulation-based heat treatment processes. The Fabricator – Heat Treating Section AZO Materials – azom.com A materials-focused site with articles and innovations in heat treatment and metallurgy. Research Journals Journal of Heat Treating – Springer Focused on new developments in thermal processes and material properties. Journal of Materials Processing Technology – Elsevier Covers modeling, processes, and innovations in heat treatment. Metallurgical and Materials Transactions A – TMS/Wiley Peer-reviewed journal with in-depth scientific studies on heat treatment effects. YouTube Educational Channels MIT OpenCourseWare – Materials Science YouTube Playlist on Materials & Heat Treatment Practical Engineering Explains technical processes in a visual and digestible way (search for “steel hardening” or “heat treatment”). The Engineering Mindset Clear, animated videos on mechanical and materials topics, including heat treatment. This article was written: October 2, 2024 Updated: July 9, 2025. By Mr. Godwin David Chief Editor @Mechanical Lesson. A project’s chance of success is reliant on the type of screws used. Metal screws … Read more Engineering and manufacturing professionals are searching for sustainable solutions and innovative materials. Recycled concrete aggregate … Read more In high-speed machining, thermal expansion of aluminum becomes a significant problem. As opposed to steel, … Read more Waiting on the side of the road with a flat tire is no fun. Once … Read more The dealership lot is filled with new cars all equipped with screens, sensors and stylish … Read more Fast, cost-efficient, eco-friendly – modular construction has everything building companies ever wished for. It has … Read more Bringing claims against large trucking companies comes with both legal and practical barriers. These types … Read more Determining the value of your car accident claim in New York is not always easy. … Read more Your vehicle type matters in accidents. It can position you legally, develop claims complexity, and … Read more Self-driving cars are not a fantasy anymore. They are on the street, traversing traffic, making … Read more Assigning fault in an auto accident requires looking at the facts, evidence, and laws relevant … Read more Road design matters because they affect drivers behavior, visibility and flow of traffic when accidents … Read more Accuracy in automotive parts shipping and manufacturing is critical – even a few microns in … Read more There are many reasons why your car may not start, but what does it mean … Read more Every successful product you see started as a rough idea before it became a model … Read more In this article, you learn what is the heat treatment process. Its methods, types, purpose, procedure, and application of heat treatment.Heat treatment is an operation involving heating and cooling a metal or an alloy in the solid state to obtain certain desirable properties without changing composition. It is an essential operation in the manufacturing process of machine parts and tools.The process of heat treatment is carried out to change the grain size, modify the structure of the material, and relieve the stresses set up by the material after hot or cold work.The heat treatment is done to improve the machinability.To improve magnetic and electrical properties.To increase resistance to wear, heat, corrosion, and much more reason.Heat treatment consists of heating the metal near or above its critical temperature, held for a particular time at finally cooling the metal in some medium which may be air, water, brine, or molten salts. The heat treatment process includes annealing, case hardening, tempering, normalizing and quenching, nitriding, cyaniding, etc.Checkout: The Complete List of Mechanical Properties of MaterialsThere are three fundamental steps in the heat treatment process. All of these heat-treating processes include heating and cooling steel.However, there are differences in the procedures in terms of the outcomes, the cooling rates, and the heating temperatures used.A lot of heat treatments start with the steel being heated to a set temperature, known as the austenitizing temperature, which is determined by the composition of the steel, and the heat treatment is applied to the steel, such as annealing, normalizing, hardening, etc.The type of heat treatment that is used will depend on the desired properties of the steel.It keeps the steel at the austenitizing temperature for a set period while preventing grain growth. In soaking time, the pre-existing phases transform into fine-grained, homogeneous austenite without grain development throughout the entire component (including the center).The fixed cooling rate of a component is determined by:Heat treatment is applied to the alloy fixed according to what properties the steel will finally gain.Steel composition.The thickness of the part.Following are the different types of heat treatment processes:AnnealingNormalizinghardeningTemperingNitridingCyanidingInduction HardeningFlame HardeningRead Also: What is the Metal Casting Process? A Complete GuideAnnealing is one of the most important processes of heat treatment. It is one of the most widely used operations in the heat treatment of iron and steel and is defined as the softening process.Heating from 30 – 50°C above the upper critical temperature and cooling it at a very slow rate by seeking it the furnace. The main aim of annealing is to make steel more ductile and malleable and to remove internal stresses. This process makes the steel soft so that it can be easily machined.It softens steel and improves its machinability.To refine grain size and remove gases.It removes the internal stresses developed during the previous process.To obtain desired ductility, malleability, and toughness.It modifies the electrical and magnetic properties.Depending on the carbon content, the steel is heated to a temperature of about 50° to 55°C above its critical temperature range. It is held at this temperature for a definite period depending on the type of furnace and nature of work. The steel is then allowed to cool inside the furnace constantly.It is applied to castings and forgings.Normalizing: The main aim of normalizing is to remove the internal stresses developed after the cold working process. In this, steel is heated 30 – 50°C above its upper critical temperature and cooled in the air.It improves mechanical and electrical properties, machinability & tensile strength. Normalizing is the process of heat treatment carried out to restore the structure of normal conditions.Promote uniformity of structure.To secure grain refinement.To bring about desirable changes in the properties of steel.The steel is heated to a temperature of about 40° to 50°C above its upper critical temperature. It is held at this temperature for a short duration. The steel is then allowed to cool in still air at room temperature, which is known as air quenching.It is applied castings and forgings to refine grain structure and to relieve stresses.It is applied after cold work such as rolling, stamping, and hammering.Read Also: Different Types of Metals and Their Properties [Complete Guide]Hardening: The main aim of the hardening process is to make steel hard. In this process, steel is heated 30° – 40°C above the upper critical temperature and then followed by continued cooling to room temperature by quenching in water or oil. It is the opposite process of annealing.By hardening, it increases the hardness of steel.To resist to wearAllows the steel to cut other metalsThe steel is heated above its critical temperature range. It is held at that temperature for a definite period. The steel is then rapidly cooled in a medium of quenching.The quenching medium is selected according to the degree of hardness desired. The air, water, brine, oils, and molten salts are used as quenching mediums. A thin section such knife blades are cooled in the air. Water is a widely used medium but it results in the formation of bubbles on the surface of the metal.Hence brine solution is used to prevent this. Oil is used when there is a risk of distortion on cracks and is suitable for alloy steels. The molten salts are used to cool thin sections to obtain crack-free and impact-resistant products.It is applied for chisels, sledgehammers, hand hammers, center punches, taps, dies, milling cutters, knife blades, and gears.Tempering: When the hardening process hardens a steel specimen, it becomes brittle and has high residual stress. It is an operation used to modify the properties of steel hardened by quenching to increase its usefulness.Tempering or drawing results in a reduction of brittleness and removal of internal strains caused during hardening. Steel must be tempered after the hardening process.The tempering is divided into three categories according to the usefulness of steel required.Low-temperature tempering.Medium temperature tempering.High-temperature tempering.To relieve internal stress caused by hardening.To reduce brittleness.Improve ductility, strength, and toughness.To increase wear resistance.To obtain desired mechanical properties.The steel after being quenched in the hardening process is reheated to a temperature slightly above the temperature range at which it is to be used, but below the lower critical temperature. The temperature here varies from 100°C to 700°C.The reheating is done in a bath of oil molten lead or molten salt. The specimen is held in the bath for some time till attains the temperature evenly, the time depends on the composition and desired quality of the steel. Now the specimen is removed from the bath and allowed to cool slowly in still air.It is applied to cutting tools, tools, and gears, which are hardened by the hardening process.Read Also: Types of Sheet Metal Operations with Diagrams [Explained]Nitriding is the process of the case or surface hardening in which nitrogen gas is employed to obtain the hard skin of the metal. In this process, steel is heated in the presence of an ammonia environment.Due to this, a nitrogen atom is deposited, making the material hard. Induction-hardening and flame-hardening objects are heated by an oxy-acetylene flame.To harden the surface of the steel to a certain depth.Increase resistance to wear and fatigue.To increase corrosion resistance.It is done in the electric furnace where a temperature varying between 450° and 510°C is maintained. The part is well machined and finished and placed in an airtight container provided with outlet and inlet tubes through which ammonia gas is circulated.The container with the part is placed in the furnace and ammonia gas is passed through it while the furnace is heated.During the process of heating nitrogen gas is released from ammonia in the form of atomic nitrogen, which reacts with the surface of the part, and forms iron nitrate.The depth of entrance depends upon the length of time spent at the nitriding temperature. The part is taken out and it does not require any quenching or further heat treatment.It is applied for hardening the surface of medium carbon alloy steels.In this process, steel is heated in the presence of a sodium cyanide environment. Due to this, carbon and nitrogen atoms are deposited on the surface of steel and make it hard.This method is effective for increasing the fatigue limit of medium and small-sized parts such as gears, shafts, wrist pins, etc.To increase surface hardness.increase wear resistance.To give a clean, bright, and pleasing appearance to the hardened surface.The parts to be treated are dipped in a molten cyanide salt bath maintained at a temperature of 950°C. The molten salts used are sodium chloride, sodium carbonate, sodium cyanide, and soda ash.The immersed article is left in the molten cyanide salt at a temperature of 950°C for about 15 to 20 minutes. The decomposition of sodium cyanide yields nitrogen and carbon from carbon monoxide, which is diffused into the surface resulting in hardening the surface. The part is then taken out of the bath and quenched in water or oil.It is applied to small articles like gears, bushing, screws, pins, and small hand tools, which require a thin and hard wear-resisting surface.Read Also: Gear Cutting: Its Types, Advantages, DisadvantagesCarburising: In this process, steel is heated in a carbon environment. Due to this carbon atoms are deposited on the metal surface and make it hard.The main aim of this process is to make the only external surface of steel hard and the inner core soft. It is the process of carburisation i.e., saturating the surface layer of steel with carbon, or some other process by which case is hardened and the core remains soft.To obtain a hard and wear resistance to machine parts.By case hardening, it obtains a tough core.To obtain a higher fatigue limit and high mechanical properties in the core.The following are the purposes of heat treatment.Improve mechanical properties such as tensile strength, hardness, ductility, shock resistance, and corrosion resistance.Improve machinability.To relieve the internal stresses of the metal induced during cold or hot working.To change or refine grain size.Improve magnetic and electric properties.Increase resistance to wear, and corrosion.To increase the surface hardness.Download PDF of this articleThat’s it thanks for reading. So now, we hope that we have cleared all your doubts about the Heat Treatment Process. If you still have doubts about the “Heat Treatment Process”, you can ask in the comments. If you like our article, then please share it with your friends.Subscribe to our newsletter to get notified when we upload new posts.Read More About Mechanical Engg on our Site:What is the heat treatment process?Heat treatment is a combination of heating and cooling that produces desired properties in metals or alloys in their solid state.What are the 4 common types of heat treatment processes?There are several common types of heat treatment processes, each of which achieves a different result, such as annealing, hardening, quenching, and stress relieving.What is the temperature of annealing?A partial transformation to austenite occurs during intermediate annealing, which is done at 649°C to 760°C / 1200°F to 1400°F. Full annealing, on the other hand, includes fully austenitizing the work at 816°C to 927°C / 1500°F to 1700°F.What is the quenching process?In quenching, a metal object is quickly cooled from the high temperature at which it has been shaped, such as by immersion in oil or water. Heat treatment is a vital process across many industries—from automotive and construction to oil and gas and aerospace. By carefully heating and cooling metals under controlled conditions, heat treatment enhances their mechanical properties, such as hardness, strength, ductility, and resistance to wear or corrosion.This complete guide explores what heat treatment is, how it works, the different types, and why it’s essential in industrial applications. Whether you’re an engineer, QA/QC officer, or project manager, this article will help you understand why heat treatment is a non-negotiable part of modern manufacturing and infrastructure development.Heat treatment is the process of heating and cooling metals in a controlled environment to alter their microstructure and improve their mechanical and physical properties without changing the material’s shape. The purpose varies depending on the application—from increasing tensile strength and hardness to relieving internal stress or enhancing wear resistance.The process is often performed using high-precision equipment like a fixed furnace or through local PWHT (Post Weld Heat Treatment) on-site, depending on the scope and complexity of the project.Heat treatment isn’t just a supplementary step—it’s a critical quality assurance tool. Without proper heat treatment, metal components can suffer from structural failure, cracking, brittleness, or reduced load capacity.Enhances strength, toughness, and hardnessReduces internal stress caused by welding or machiningImproves machinability and formabilityIncreases resistance to extreme temperatures, wear, and corrosionRefines grain structure for long-term durabilityA softening process where metals are heated and slowly cooled to increase ductility and reduce hardness, ideal for carbon steel and non-ferrous metals.Involves heating steel above critical temperature and cooling it in open air to achieve uniform grain structure and improved mechanical properties.Metal is heated and rapidly cooled using water, oil, or air to increase hardness and tensile strength.Conducted after quenching to reduce brittleness and restore toughness by reheating the metal to a lower temperature.A process to reduce residual stresses from welding, machining, or forming, without significantly altering material hardness.Critical for welding-heavy applications such as pressure vessels and piping systems in the oil and gas sector. PWHT helps eliminate residual stresses and restore material integrity.Heat treatment is indispensable for high-pressure pipelines, offshore structures, and pressure vessels, especially using local PWHT or furnace-based heat treatment to meet ASME and API standards.Engine parts like gears, crankshafts, and axles undergo heat treatment to ensure they can withstand high loads, impacts, and friction.Steel frameworks and weld joints in buildings, bridges, and industrial facilities need heat treatment to ensure they remain reliable under structural stress and environmental changes.Aluminum and titanium alloys used in aircraft manufacturing are heat-treated to maintain strength while keeping the weight low, ensuring safety and fuel efficiency.Depending on the industry, heat treatment is governed by international codes and standards to ensure safety and quality:ASME Section VIII – For pressure vesselsAPI 650 / API 653 – For oil and gas storage tanksAWS D1.1 – For welded steel structuresISO 9001 & ISO 17663 – For quality management and documentation of heat treatmentTo get optimal results, working with an experienced and certified heat treatment provider is key. PT. Bainita Heat Industry is a leading heat treatment company in Indonesia, trusted by major players in the oil and gas, construction, and manufacturing sectors.Fixed Furnace Heat TreatmentOnsite Local PWHT ServicesNormalizing, Stress Relieving, and TemperingHardness Testing & Non-Destructive Testing (NDT)Metallurgical Consulting ServicesAll our heat treatment services are supervised by certified engineers and documented with comprehensive reports (TTC, MTC, Hardness Test Results) to ensure full compliance with international standards.Heat treatment is not merely a process—it’s a strategic investment in the reliability, longevity, and performance of your materials and equipment. Whether you’re in heavy industry or high-precision manufacturing, proper heat treatment ensures your products stand the test of time, pressure, and performance.To request a consultation, quote, or site inspection, contact our team at:PT. Bainita Heat Industry – Reliable Heat Treatment Services for Mission-Critical Projects. Reports, developments, and new products to keep you aware of what’s happening with colleagues and businesses around the world. Process of heating something to alter it Heat treating furnace at 1,800 °F (980 °C) Heat treating (or heat treatment) is a group of industrial, thermal and metalworking processes used to alter the physical, and sometimes chemical, properties of a material. The most common application is metallurgical. Heat treatments are also used in the manufacture of many other materials, such as glass. Heat treatment involves the use of heating or chilling, normally to extreme temperatures, to achieve the desired result such as hardening or softening of a material. Heat treatment techniques include annealing, case hardening, precipitation strengthening, tempering, carburizing, normalizing and quenching. Although the term heat treatment applies only to processes where the heating and cooling are done for the specific purpose of altering properties intentionally, heating and cooling often occur incidentally during other manufacturing processes such as hot forming or welding. Allotropes of iron, showing the differences in lattice structures between alpha iron (low temperature) and gamma iron (high temperature). The alpha iron has no spaces for carbon atoms to reside, while the gamma iron is open to the free movement of small carbon atoms. Photomicrographs of steel. Top: In annealed (slowly cooled) steel, the carbon precipitates forming layers of ferrite (iron) and cementite (carbide). Bottom: In quenched (quickly cooled) steel, the carbon remains trapped in the iron, creating great internal stresses in the needle or plate-like grains. Metallic materials consist of a microstructure of small crystals called "grains" or crystallites. The nature of the grains (i.e. grain size and composition) is one of the most effective factors that can determine the overall mechanical behavior of the metal. Heat treatment provides an efficient way to manipulate the properties of the metal by controlling the rate of diffusion and the rate of cooling within the microstructure. Heat treating is often used to alter the mechanical properties of a metallic alloy, manipulating properties such as the hardness, strength, toughness, ductility, and elasticity.[1] There are two mechanisms that may change an alloy's properties during heat treatment: the formation of martensite causes the crystals to deform intrinsically, and the diffusion mechanism causes changes in the homogeneity of the alloy.[2] The crystal structure consists of atoms that are grouped in a very specific arrangement, called a lattice. In most elements, this order will rearrange itself, depending on conditions like temperature and pressure. This rearrangement called allotropy or polymorphism, may occur several times, at many different temperatures for a particular metal. In alloys, this rearrangement may cause an element that will not normally dissolve into the base metal to suddenly become soluble, while a reversal of the allotropy will make the elements either partially or completely insoluble.[3] When in the soluble state, the process of diffusion causes the atoms of the dissolved element to spread out, attempting to form a homogenous distribution within the crystals of the base metal. If the alloy is cooled to an insoluble state, the atoms of the dissolved constituents (solutes) may migrate out of the solution. This type of diffusion, called precipitation, leads to nucleation, where the migrating atoms group together at the grain-boundaries. This forms a microstructure generally consisting of two or more distinct phases.[4] For instance, steel that has been heated above the austenizing temperature (red to orange-hot, or around 1,500 °F (820 °C) to 1,600 °F (870 °C) depending on carbon content), and then cooled slowly, forms a laminated structure composed of alternating layers of ferrite and cementite, becoming soft pearlite.[5] After heating the steel to the austenite phase and then quenching it in water, the microstructure will be in the martensitic phase. This is due to the fact that the steel will change from the austenite phase to the martensite phase after quenching. Some pearlite or ferrite may be present if the quench did not rapidly cool off all the steel.[4] Unlike iron-based alloys, most heat-treatable alloys do not experience a ferrite transformation. In these alloys, the nucleation at the grain-boundaries often reinforces the structure of the crystal matrix. These metals harden by precipitation. Typically a slow process, depending on temperature, this is often referred to as "age hardening".[6] Many metals and non-metals exhibit a martensite transformation when cooled quickly (with external media like oil, polymer, water, etc.). When a metal is cooled very quickly, the insoluble atoms may not be able to migrate out of the solution in time. This is called a "diffusionless transformation." When the crystal matrix changes to its low-temperature arrangement, the atoms of the solute become trapped within the lattice. The trapped atoms prevent the crystal matrix from completely changing into its low-temperature allotrope, creating shearing stresses within the lattice. When some alloys are cooled quickly, such as steel, the martensite transformation hardens the metal, while in others, like aluminum, the alloy becomes softer.[7][8] Phase diagram of an iron-carbon alloying system. Phase changes occur at different temperatures (vertical axis) for different compositions (horizontal axis). The dotted lines mark the eutectoid (A) and eutectic (B) compositions. The specific composition of an alloy system will usually have a great effect on the results of heat treating. If the percentage of each constituent is just right, the alloy will form a single, continuous microstructure upon cooling. Such a mixture is said to be eutectoid. However, If the percentage of the solutes varies from the eutectoid mixture, two or more different microstructures will usually form simultaneously. A hypo eutectoid solution contains less of the solute than the eutectoid mix, while a hypereutectoid solution contains more.[9] A eutectoid (eutectic-like) alloy is similar in behavior to a eutectic alloy. A eutectic alloy is characterized by having a single melting point. This melting point is lower than that of any of the constituents, and no change in the mixture will lower the melting point any further. When a molten eutectic alloy is cooled, all of the constituents will crystallize into their respective phases at the same temperature. A eutectoid alloy is similar, but the phase change occurs, not from a liquid, but from a solid solution. Upon cooling a eutectoid alloy from the solution temperature, the constituents will separate into different crystal phases, forming a single microstructure. A eutectoid steel, for example, contains 0.77% carbon. Upon cooling slowly, the solution of iron and carbon (a single phase called austenite) will separate into platelets of the phases ferrite and cementite. This forms a layered microstructure called pearlite. Since pearlite is harder than iron, the degree of softness achievable is typically limited to that produced by the pearlite. Similarly, the hardenability is limited by the continuous martensitic microstructure formed when cooled very fast.[10] A hypoeutectic alloy has two separate melting points. Both are above the eutectic melting point for the system but are below the melting points of any constituent forming the system. Between these two melting points, the alloy will exist as part solid and part liquid. The constituent with the higher melting point will solidify first. When completely solidified, a hypoeutectic alloy will often be in a solid solution. Similarly, a hypoeutectoid alloy has two critical temperatures, called "arrests". Between these two temperatures, the alloy will exist partly as the solution and partly as a separate crystallizing phase, called the "pro eutectoid phase". These two temperatures are called the upper (A3) and lower (A1) transformation temperatures. As the solution cools from the upper transformation temperature toward an insoluble state, the excess base metal will often be forced to "crystallize-out", becoming the pro eutectoid. This will occur until the remaining concentration of solutes reaches the eutectoid level, which will then crystallize as a separate microstructure. For example, a hypoeutectoid steel contains less than 0.77% carbon. Upon cooling a hypoeutectoid steel from the austenite transformation temperature, small islands of proeutectoid-ferrite will form. These will continue to grow and the carbon will recede until the eutectoid concentration in the rest of the steel is reached. This eutectoid mixture will then crystallize as a microstructure of pearlite. Since ferrite is softer than pearlite, the two microstructures combine to increase the ductility of the alloy. Consequently, the hardenability of the alloy is lowered.[11] Hypereutectic alloys A hypereutectic alloy also has different melting points. However, between these points, it is the constituent with the higher melting point that will be solid. Similarly, a hypereutectoid alloy has two critical temperatures. When cooling a hypereutectoid alloy from the upper transformation temperature, it will usually be the excess solutes that crystallize-out first, forming the pro-eutectoid. This continues until the concentration in the remaining alloy becomes eutectoid, which then crystallizes into a separate microstructure. A hypereutectoid steel contains more than 0.77% carbon. When slowly cooling hypereutectoid steel, the cementite will begin to crystallize first. When the remaining steel becomes eutectoid in composition, it will crystallize into pearlite. Since cementite is much harder than pearlite, the alloy has greater hardenability at a cost in ductility.[9][11] Time-temperature transformation (TTT) diagram for steel. The red curves represent different cooling rates (velocity) when cooled from the upper critical (A3) temperature. V1 (quenching) produces martensite. V2 (normalizing) produces both pearlite and martensite, V3 (annealing) produces bainite mixed with pearlite. Proper heat treating requires precise control over temperature, time held at a certain temperature and cooling rate.[12] With the exception of stress-relieving, tempering, and aging, most heat treatments begin by heating an alloy beyond a certain transformation, or arrest (A), temperature. This temperature is referred to as an "arrest" because at the A temperature the metal experiences a period of hysteresis. At this point, all of the heat energy is used to cause the crystal change, so the temperature stops rising for a short time (arrests) and then continues climbing once the change is complete.[13] Therefore, the alloy must be heated above the critical temperature for a transformation to occur. The alloy will usually be held at this temperature long enough for the heat to completely penetrate the alloy, thereby bringing it into a complete solid solution. Iron, for example, has four critical-temperatures, depending on carbon content. Pure iron in its alpha (room temperature) state changes to nonmagnetic gamma-iron at its A2 temperature, and weldable delta-iron at its A4 temperature. However, as carbon is added, becoming steel, the A2 temperature splits into the A3 temperature, also called the austenizing temperature (all phases become austenite, a solution of gamma iron and carbon) and its A1 temperature (austenite changes into pearlite upon cooling). Between these upper and lower temperatures the pro eutectoid phase forms upon cooling. Because a smaller grain size usually enhances mechanical properties, such as toughness, shear strength and tensile strength, these metals are often heated to a temperature that is just above the upper critical temperature, in order to prevent the grains of solution from growing too large. For instance, when steel is heated above the upper critical-temperature, small grains of austenite form. These grow larger as the temperature is increased. When cooled very quickly, during a martensite transformation, the austenite grain-size directly affects the martensitic grain-size. Larger grains have large grain-boundaries, which serve as weak spots in the structure. The grain size is usually controlled to reduce the probability of breakage.[14] The diffusion transformation is very time-dependent. Cooling a metal will usually suppress the precipitation to a much lower temperature. Austenite, for example, usually only exists above the upper critical temperature. However, if the austenite is cooled quickly enough, the transformation may be suppressed for hundreds of degrees below the lower critical temperature. Such austenite is highly unstable and, if given enough time, will precipitate into various microstructures of ferrite and cementite. The cooling rate can be used to control the rate of grain growth or can even be used to produce partially martensitic microstructures.[15] However, the martensite transformation is time-independent. If the alloy is cooled to the martensite transformation (Ms) temperature before other microstructures can fully form, the transformation will usually occur at just under the speed of sound.[16] When austenite is cooled but kept above the martensite start temperature Ms so that a martensite transformation does not occur, the austenite grain size will have an effect on the rate of nucleation, but it is generally temperature and the rate of cooling that controls the grain size and microstructure. When austenite is cooled extremely slowly, it will form large ferrite crystals filled with spherical inclusions of cementite. This microstructure is referred to as "sphereoidite". If cooled a little faster, then coarse pearlite will form. Even faster, and fine pearlite will form. If cooled even faster, bainite will form, with more complete bainite transformation occurring depending on the time held above martensite start Ms. Similarly, these microstructures will also form, if cooled to a specific temperature and then held there for a certain time.[17] Most non-ferrous alloys are also heated in order to form a solution. Most often, these are then cooled very quickly to produce a martensite transformation, putting the solution into a supersaturated state. The alloy, being in a much softer state, may then be cold worked. This causes work hardening that increases the strength and hardness of the alloy. Moreover, the defects caused by plastic deformation tend to speed up precipitation, increasing the hardness beyond what is normal for the alloy. Even if not cold worked, the solutes in these alloys will usually precipitate, although the process may take much longer. Sometimes these metals are then heated to a temperature that is below the lower critical (A1) temperature, preventing recrystallization, in order to speed-up the precipitation.[18][19][20] Steel castings after undergoing 12-hour 1,200 °C (2,190 °F) heat treatment. Complex heat treating schedules, or "cycles", are often devised by metallurgists to optimize an alloy's mechanical properties. In the aerospace industry, a superalloy may undergo five or more different heat treating operations to develop the desired properties. [citation needed] This can lead to quality problems depending on the accuracy of the furnace's temperature controls and timer. These operations can usually be divided into several basic techniques. Main article: Annealing (metallurgy) Annealing consists of heating a metal to a specific temperature and then cooling at a rate that will produce a refined microstructure, either fully or partially separating the constituents. The rate of cooling is generally slow. Annealing is most often used to soften a metal for cold working, to improve machinability, or to enhance properties like electrical conductivity. In ferrous alloys, annealing is usually accomplished by heating the metal beyond the upper critical temperature and then cooling very slowly, resulting in the formation of pearlite. In both pure metals and many alloys that cannot be heat treated, annealing is used to remove the hardness caused by cold working. The metal is heated to a temperature where recrystallization can occur, thereby repairing the defects caused by plastic deformation. In these metals, the rate of cooling will usually have little effect. Most non-ferrous alloys that are heat-treatable are also annealed to relieve the hardness of cold working. These may be slowly cooled to allow full precipitation of the constituents and produce a refined microstructure. Ferrous alloys are usually either "full annealed" or "process annealed". Full annealing requires very slow cooling rates, in order to form coarse pearlite. In process annealing, the cooling rate may be faster; up to, and including normalizing. The main goal of process annealing is to produce a uniform microstructure. Non-ferrous alloys are often subjected to a variety of annealing techniques, including "recrystallization annealing", "partial annealing", "full annealing", and "final annealing". Not all annealing techniques involve recrystallization, such as stress relieving.[21] Normalizing is a technique used to provide uniformity in grain size and composition (equiaxed crystals) throughout an alloy. The term is often used for ferrous alloys that have been austenitized and then cooled in the open air.[21] Normalizing not only produces pearlite but also martensite and sometimes bainite, which gives harder and stronger steel but with less ductility for the same composition than full annealing. In the normalizing process the steel is heated to about 40 degrees Celsius above its upper critical temperature limit, held at this temperature for some time, and then cooled in air. Stress-relieving is a technique to remove or reduce the internal stresses created in metal. These stresses may be caused in a number of ways, ranging from cold working to non-uniform cooling. Stress-relieving is usually accomplished by heating a metal below the lower critical temperature and then cooling uniformly.[21] Stress relieving is commonly used on items like air tanks, boilers and other pressure vessels, to remove a portion of the stresses created during the welding process.[22] Main article: Precipitation hardening Some metals are classified as precipitation hardening metals. When a precipitation hardening alloy is quenched, its alloying elements will be trapped in solution, resulting in a soft metal. Aging a "solutionized" metal will allow the alloying elements to diffuse through the microstructure and form intermetallic particles. These intermetallic particles will nucleate and fall out of the solution and act as a reinforcing phase, thereby increasing the strength of the alloy. Alloys may age " naturally" meaning that the precipitates form at room temperature, or they may age "artificially" when precipitates only form at elevated temperatures. In some applications, naturally aging alloys may be stored in a freezer to prevent hardening until after further operations - assembly of rivets, for example, maybe easier with a softer part. Examples of precipitation hardening alloys include 2000 series, 6000 series, and 7000 series aluminium alloy, as well as some superalloys and some stainless steels. Steels that harden by aging are typically referred to as maraging steels, from a combination of the term "martensite aging".[21] Main article: Quenching Quenching is a process of cooling a metal at a rapid rate. This is most often done to produce a martensite transformation. In ferrous alloys, this will often produce a harder metal, while non-ferrous alloys will usually become softer than normal. To harden by quenching, a metal (usually steel or cast iron) must be heated above the upper critical temperature (Steel: above 815~900 degrees Celsius[23]) and then quickly cooled. Depending on the alloy and other considerations (such as concern for maximum hardness vs. cracking and distortion), cooling may be done with forced air or other gases, (such as nitrogen). Liquids may be used, due to their better thermal conductivity, such as oil, water, a polymer dissolved in water, or a brine. Upon being rapidly cooled, a portion of austenite (dependent on alloy composition) will transform to martensite, a hard, brittle crystalline structure. The quenched hardness of a metal depends on its chemical composition and quenching method. Cooling speeds, from fastest to slowest, go from brine, polymer (i.e. mixtures of water + glycol polymers), freshwater, oil, and forced air. However, quenching certain steel too fast can result in cracking, which is why high-tensile steels such as AISI 4140 should be quenched in oil, tool steels such as ISO 1.2767 or H13 hot work tool steel should be quenched in forced air, and low alloy or medium-tensile steels such as XK1320 or AISI 1040 should be quenched in brine. Some Beta titanium based alloys have also shown similar trends of increased strength through rapid cooling.[24] However, most non-ferrous metals, like alloys of copper, aluminum, or nickel, and some high alloy steels such as austenitic stainless steel (304, 316), produce an opposite effect when these are quenched: they soften. Austenitic stainless steels must be quenched to become fully corrosion resistant, as they work-harden significantly.[21] Main article: Tempering (metallurgy) Untempered martensitic steel, while very hard, is too brittle to be useful for most applications. A method for alleviating this problem is called tempering. Most applications require that quenched parts be tempered. Tempering consists of heating steel below the lower critical temperature, (often from 400˚F to 1105˚F or 205˚C to 595˚C, depending on the desired results), to impart some toughness. Higher tempering temperatures (maybe up to 1,300˚F or 700˚C, depending on the alloy and application) are sometimes used to impart further ductility, although some yield strength is lost. Tempering may also be performed on normalized steels. Other methods of tempering consist of quenching to a specific temperature, which is above the martensite start temperature, and then holding it there until pure bainite can form or internal stresses can be relieved. These include austempering and martempering.[21] Tempering colors of steel Steel that has been freshly ground or polished will form oxide layers when heated. At a very specific temperature, the iron oxide will form a layer with a very specific thickness, causing thin-film interference. This causes colors to appear on the surface of the steel. As the temperature is increased, the iron oxide layer grows in thickness, changing the color.[25] These colors, called tempering colors, have been used for centuries to gauge the temperature of the metal.[26] 350˚F (176˚C), light yellowish 400˚F (204˚C), light-straw 440˚F (226˚C), dark-straw 500˚F (260˚C), brown 540˚F (282˚C), purple 590˚F (310˚C), deep blue 640˚F (337˚C), light blue[26] The tempering colors can be used to judge the final properties of the tempered steel. Very hard tools are often tempered in the light to the dark straw range, whereas springs are often tempered to the blue. However, the final hardness of the tempered steel will vary, depending on the composition of the steel. Higher-carbon tool steel will remain much harder after tempering than spring steel (of slightly less carbon) when tempered at the same temperature. The oxide film will also increase in thickness over time. Therefore, steel that has been held at 400˚F for a very long time may turn brown or purple, even though the temperature never exceeded that needed to produce a light straw color. Other factors affecting the final outcome are oil films on the surface and the type of heat source used.[26] Main article: Differential heat treatment Many heat treating methods have been developed to alter the properties of only a portion of an object. These tend to consist of either cooling different areas of an alloy at different rates, by quickly heating in a localized area and then quenching, by thermochemical diffusion, or by tempering different areas of an object at different temperatures, such as in differential tempering. [citation needed] Main article: Differential hardening A differentially hardened katana. The bright, wavy line following the hamon, called the nioi, separates the martensitic edge from the pearlitic back. The inset shows a close-up of the nioi, which is made up of individual martensite grains (niye) surrounded by pearlite. The wood-grain appearance comes from layers of different compositions.Some techniques allow different areas of a single object to receive different heat treatments. This is called differential hardening. It is common in high quality knives and swords. The Chinese jian is one of the earliest known examples of this, and the Japanese katana may be the most widely known. The Nepalese Khukuri is another example. This technique uses an insulating layer, like layers of clay, to cover the areas that are to remain soft. The areas to be hardened are left exposed, allowing only certain parts of the steel to fully harden when quenched. [citation needed] Main article: Surface hardening Flame hardening is used to harden only a portion of a metal. Unlike differential hardening, where the entire piece is heated and then cooled at different rates, in flame hardening, only a portion of the metal is heated before quenching. This is usually easier than differential hardening, but often produces an extremely brittle zone between the heated metal and the unheated metal, as cooling at the edge of this heat-affected zone is extremely rapid. [citation needed] Main article: Induction hardening Induction hardening is a surface hardening technique in which the surface of the metal is heated very quickly, using a no-contact method of induction heating. The alloy is then quenched, producing a martensite transformation at the surface while leaving the underlying metal unchanged. This creates a very hard, wear-resistant surface while maintaining the proper toughness in the majority of the object. Crankshaft journals are a good example of an induction hardened surface.[27] Main article: Case hardening Case hardening is a thermochemical diffusion process in which an alloying element, most commonly carbon or nitrogen, diffuses into the surface of a monolithic metal. The resulting interstitial solid solution is harder than the base material, which improves wear resistance without sacrificing toughness.[21] Laser surface engineering is a surface treatment with high versatility, selectivity and novel properties. Since the cooling rate is very high in laser treatment, metastable even metallic glass can be obtained by this method. Main article: Cryogenic treatment Although quenching steel causes the austenite to transform into martensite, all of the austenite usually does not transform. Some austenite crystals will remain unchanged even after quenching below the martensite finish (Mf) temperature. Further transformation of the austenite into martensite can be induced by slowly cooling the metal to extremely low temperatures. Cold treating generally consists of cooling the steel to around -115˚F (-81˚C), but does not eliminate all of the austenite. Cryogenic treating usually consists of cooling to much lower temperatures, often in the range of -315˚F (-192˚C), to transform most of the austenite into martensite. Cold and cryogenic treatments are typically done immediately after quenching, before any tempering, and will increase the hardness, wear resistance, and reduce the internal stresses in the metal but, because it is really an extension of the quenching process, it may increase the chances of cracking during the procedure. The process is often used for tools, bearings, or other items that require good wear resistance. However, it is usually only effective in high-carbon or high-alloy steels in which more than 10% austenite is retained after quenching.[28][29] The heating of steel is sometimes used as a method to alter the carbon content. When steel is heated in an oxidizing environment, the oxygen combines with the iron to form an iron-oxide layer, which protects the steel from decarburization. When the steel turns to austenite, however, the oxygen combines with iron to form a slag, which provides no protection from decarburization. The formation of slag and scale actually increases decarburization, because the iron oxide keeps oxygen in contact with the decarburization zone even after the steel is moved into an oxygen-free environment, such as the coals of a forge. Thus, the carbon atoms begin combining with the surrounding scale and slag to form both carbon monoxide and carbon dioxide, which is released into the air. Steel contains a relatively small percentage of carbon, which can migrate freely within the gamma iron. When austenitized steel is exposed to air for long periods of time, the carbon content in the steel can be lowered. This is the opposite from what happens when steel is heated in a reducing environment, in which carbon slowly diffuses further into the metal. In an oxidizing environment, the carbon can readily diffuse outwardly, so austenitized steel is very susceptible to decarburization. This is often used for cast steel, where a high carbon-content is needed for casting, but a lower carbon-content is desired in the finished product. It is often used on cast-irons to produce malleable cast iron, in a process called "white tempering". This tendency to decarburize is often a problem in other operations, such as blacksmithing, where it becomes more desirable to austenize the steel for the shortest amount of time possible to prevent too much decarburization.[30] Usually the end condition is specified instead of the process used in heat treatment.[31] A modern, fully computerised case hardening furnace. Case hardening is specified by "hardness" and "case depth". The case depth can be specified in two ways: total case depth or effective case depth. The total case depth is the true depth of the case. For most alloys, the effective case depth is the depth of the case that has a hardness equivalent of HRC50; however, some alloys specify a different hardness (40-60 HRC) at effective case depth; this is checked on a Tukon microhardness tester. This value can be roughly approximated as 65% of the total case depth; however, the chemical composition and hardenability can affect this approximation. If neither type of case depth is specified the total case depth is assumed.[31] For case hardened parts the specification should have a tolerance of at least ±0.005 in (0.13 mm). If the part is to be ground after heat treatment, the case depth is assumed to be after grinding.[31] The Rockwell hardness scale used for the specification depends on the depth of the total case depth, as shown in the table below. Usually, hardness is measured on the Rockwell "C" scale, but the load used on the scale will penetrate through the case if the case is less than 0.030 in (0.76 mm). Using Rockwell "C" for a thinner case will result in a false reading.[31] Rockwell scale required for various case depths[31] Total case depth, min. [in] Rockwell scale 0.030 C 0.024 A 0.021 45 N 0.018 30 N 0.015 15 N Less than 0.015 "File hard" For cases that are less than 0.015 in (0.38 mm) thick a Rockwell scale cannot reliably be used, so file hard is specified instead.[31] File hard is approximately equivalent to 58 HRC.[32] When specifying the hardness either a range should be given or the minimum hardness specified. If a range is specified at least 5 points should be given.[31] Only hardness is listed for through hardening. It is usually in the form of HRC with at least a five-point range.[31] The hardness for an annealing process is usually listed on the HRB scale as a maximum value.[31] It is a process to refine grain size, improve strength, remove residual stress, and affect the electromagnetic properties... Furnaces used for heat treatment can be split into two broad categories: batch furnaces and continuous furnaces. Batch furnaces are usually manually loaded and unloaded, whereas continuous furnaces have an automatic conveying system to provide a constant load into the furnace chamber.[33] Batch systems usually consist of an insulated chamber with a steel shell, a heating system, and an access door to the chamber.[33] Many basic box-type furnaces have been upgraded to a semi-continuous batch furnace with the addition of integrated quench tanks and slow-cool chambers. These upgraded furnaces are a very commonly used piece of equipment for heat-treating.[33] Also known as a " bogie hearth", the car furnace is an extremely large batch furnace. The floor is constructed as an insulated movable car that is moved in and out of the furnace for loading and unloading. The car is usually sealed using sand seals or solid seals when in position. Due to the difficulty in getting a sufficient seal, car furnaces are usually used for non-atmosphere processes. [citation needed] Fluidised bed heat treatment line Similar in type to the car furnace, except that the car and hearth are rolled into position beneath the furnace and raised by means of a motor-driven mechanism, elevator furnaces can handle large heavy loads and often eliminate the need for any external cranes and transfer mechanisms.[33] Bell furnaces have removable covers called bells, which are lowered over the load and hearth by crane. An inner bell is placed over the hearth and sealed to supply a protective atmosphere. An outer bell is lowered to provide the heat supply.[33] Furnaces that are constructed in a pit and extend to floor level or slightly above are called pit furnaces. Workpieces can be suspended from fixtures, held in baskets, or placed on bases in the furnace. Pit furnaces are suited to heating long tubes, shafts, and rods by holding them in a vertical position. This manner of loading provides minimal distortion.[33] Salt baths are used in a wide variety of heat treatment processes including neutral hardening, liquid carburising, liquid nitriding, austempering, martempering and tempering. Parts are loaded into a pot of molten salt where they are heated by conduction, giving a very readily available source of heat. The core temperature of a part rises in temperature at approximately the same rate as its surface in a salt bath.[33] Salt baths utilize a variety of salts for heat treatment, with cyanide salts being the most extensively used. Concerns about associated occupation health and safety, and expensive waste management and disposal due to their environmental effects have made the use of salt baths less attractive in recent years. Consequently, many salt baths are being replaced by more environmentally friendly fluidized bed furnaces.[34] A fluidised bed consists of a cylindrical retort made from high-temperature alloy, filled with sand-like aluminum oxide particulate. Gas (air or nitrogen) is bubbled through the oxide and the sand moves in such a way that it exhibits fluid-like behavior, hence the term fluidized. The solid-solid contact of the oxide gives very high thermal conductivity and excellent temperature uniformity throughout the furnace, comparable to those seen in a salt bath.[33] Carbon steel Carbonizing Diffusion hardening Induction hardening Retrogression heat treatment Nitriding

^ ZIA, Abdul Wasy; Zhou, Zhifeng; Po-wan, Shum.; Lawrence Li, Kwak Yan (24 January 2017). "The effect of two-step heat treatment on hardness, fracture toughness, and wear of different biased diamond-like carbon coatings". Surface and Coatings Technology. 320: 118–125. doi:10.1016/j.surfcoat.2017.01.089. ^ Shant P. Gupta (2002). Solid state phase transformations. Allied Publishers Private Limited. pp. 28–29. ^ Robert W. Cahn; Peter Haasen, eds. (1996). Physical Metallurgy. Vol. 2. Elsevier Science. pp. 10–11. ^ a b Alvarenga, H. D.; Van de Putte, T.; Van Steenberge, N.; Sietsma, J.; Terryn, H. (8 October 2014). "Influence of Carbide Morphology and Microstructure on the Kinetics of Superficial Decarburization of C-Mn Steels". Metallurgical and Materials Transactions A. 46: 123–133. doi:10.1007/s11661-014-2600-y. S2CID 136871961. ^ Physical Metallurgy 1996, pp. 136–198 ^ Gupta 2002, pp. 299–347 ^ Physical Metallurgy 1996, pp. 1508–1543 ^ Gupta 2002, pp. 501–518 ^ a b B.B. Patra; Biswajit Samantray (2011). Engineering Chemistry I. Dorling Kindersley. pp. 75–77. ^ Dossett, Jon L.; Boyer, Howard E. (2006). Practical heat treating. ASM International. pp. 17–22. ^ a b Dossett & Boyer 2006, pp. 17–22 ^ Rajan, T. V.; Sharma, C. P.; Sharma, Ashok (1992). Heat Treatment: Principles and Techniques. Prentence Hall. p. 1. ^ New Edge of the Anvil: A Resource Book for the Blacksmith by Jack Andrews --Shipjack Press 1994 Page 93--96 ^ Rajan & Sharma 1992, pp. 62–67 ^ Dossett & Boyer 2006, pp. 23–25 ^ The physics of phase transitions: concepts and applications By Pierre Papon, Jacques Leblond, Paul Herman Ernst Meijer - Springer-Verlag Berlin Heidelberg 2006 Page 66 ^ Rajan & Sharma 1992 ^ Dossett & Boyer 2006, p. 231 ^ Rajan & Sharma 1992, pp. 187–190, 321 ^ Manufacturing technology: foundry, forming and welding By Rao - Tata McGraw-Hill 1998 Page 55 ^ a b c d e f g Dossett & Boyer 2006, pp. 2–6 ^ "The National Board of Boiler and Pressure Vessel Inspectors". www.nationalboard.org. Archived from the original on 20 December 2010. Retrieved 29 April 2018. ^ Aviation Maintenance Technician Handbook (FAA-H-8983-30A ed.). Federal Aviation Administration. 2018. ^ Najdahmadi, A.; Zarei-Hanzaki, A.; Farghadani, E. (1 February 2014). "Mechanical properties enhancement in Ti–29Nb–13Ta–4.6Zr alloy via heat treatment with no detrimental effect on its biocompatibility". Materials & Design. 54: 786–791. doi:10.1016/j.matdes.2013.09.007. ISSN 0261-3069. ^ Light, its interaction with art and antiquities By Thomas B. Brill - Plenum Publishing 1980 Page 55 ^ a b c Andrews, Jack (1994). New Edge of the Anvil: a resource book for the blacksmith. pp. 98–99. ^ Surface hardening of steels: understanding the basics By Joseph R. Davis - ASM International 2002 ^ Heat treater's guide: practices and procedures for irons and steels By ASM International - ASM International 2007 Page 12-13 ^ Handbook of residual stress and deformation of steel by George E. Totten, Maurice A. H. Howes, Tatsuo Inoue - ASM International 2002 Page 331-337 ^ Steel Heat Treatment: Metallurgy and Technologies By George E. Totten -- CRC press 2007 Page 306--308 ^ a b c d e f g h i "PMPA's Designer's Guide: Heat treatment". Archived from the original on 2009-07-14. Retrieved 2009-06-19. ^ Phone interview with the quality control inspector for FPM, Elk Grove Village, IL. 06-21-2010 ^ a b c d e f g h ASM International Handbook Committee. (1991). ASM Handbook, Volume 04 - Heat Treating. ASM International. ^ "Made in the Midlands | Fluidised beds: A Green Alternative to Salt Baths". claytonholdings.madeinthemidlands.com. Archived from the original on 2016-02-07. Retrieved 2015-06-02. International Heat Treatment Magazine in English Reed-Hill, Robert (1994). Principles of Physical Metallurgy (3rd ed.). Boston: PWS Publishing. Wikimedia Commons has media related to Heat treatment. Retrieved from " Heat treatment is a critical process used in various industries to alter the properties of materials, such as metals and alloys, to enhance their mechanical, physical, and chemical characteristics. By subjecting materials to controlled heating and cooling cycles, heat treatment can significantly improve their strength, hardness, ductility, and resistance to wear and corrosion. This article aims to provide a comprehensive overview of the stages involved in heat treatment and shed light on the transformative power of this essential industrial process. Heat treatment consists of three primary phases: Phase 1: Heating Stage – Gradually heating the metal to guarantee an even temperature. Phase 2: Soaking Stage – Maintaining the metal at a specific temperature for a designated duration and then cooling it to room temperature. Phase 3: Cooling Stage – Lowering the metal's temperature to match that of the surrounding room. Example of Normalizing Heat Treatment To ensure consistent temperatures during the heating stage, the main goal is to achieve uniformity. If there is uneven heating, it can lead to distortion or cracking as one section of a component expands faster than another. The key to achieving uniform temperatures is to heat the part slowly. The rate at which a part heats up depends on various factors. One crucial factor is the metal's heat conductivity. Metals with high heat conductivity heat up faster than those with low conductivity. Additionally, the condition of the metal affects its heating rate. Hardened tools and parts should be heated at a slower rate compared to unstressed or untreated metals. Lastly, the size and cross section of the part also play a role in the heating rate. Parts with a large cross section require slower heating rates to ensure that the interior temperature remains close to the surface temperature, preventing warping or cracking. Parts with uneven cross sections may experience uneven heating, but when the heating rate is slow, they are less likely to crack or warp excessively. See also How to bend metal rod without heat After the metal reaches the appropriate temperature, it is maintained at that temperature until the desired internal structural changes occur. This process is known as soaking. The duration of time the metal is held at the desired temperature is referred to as the soaking period. The length of the soaking period depends on the metal's chemical composition and the size of the part. In the case of steel parts with uneven cross sections, the soaking period is determined by the largest section. During the soaking stage, the metal is not rapidly heated from room temperature to the final temperature. Instead, the steel is gradually heated to a temperature slightly below the point of transformation and then held at that temperature until the heat is evenly distributed throughout the metal. This process is called preheating. Subsequently, the metal is rapidly heated to reach the final required temperature. In situations where a part has a complex design, it may be necessary to preheat it at multiple temperatures to prevent cracking and excessive warping. For instance, let's consider a complex part that needs to be heated to 1500°F for hardening. This part could be slowly heated to 600°F, soaked at that temperature, then gradually heated to 1200°F and soaked again. Finally, the part should be rapidly heated to the hardening temperature of 1500°F. It is important to note that nonferrous metals are typically not preheated since they usually do not require it, and preheating can lead to an increase in grain size for these metals. To complete the heat-treating process, a metal that has been soaked needs to be brought back to room temperature. This can be achieved by cooling the metal using a cooling medium, which can be a gas, liquid, solid, or a combination of these. The speed at which the metal cools depends on the specific metal and the desired properties. The choice of cooling medium plays a crucial role in determining the desired properties, as it affects the rate of cooling. See also Heat Treatment of MetalsQuenching is the technique used to rapidly cool metal by immersing it in oil, water, brine, or another suitable medium. Although quenching is commonly associated with hardening, as most metals are rapidly cooled during this process, it does not always result in increased hardness. For instance, copper is usually quenched in water to anneal it. On the other hand, certain metals like air-hardened steels are cooled at a slower rate for hardening purposes. During quenching, some metals are prone to cracking or warping, while others are unaffected. Therefore, the choice of quenching medium must be tailored to the specific metal. Brine or water is used for metals that require rapid cooling, while oil mixtures are more suitable for metals that need a slower cooling rate. Typically, carbon steels are hardened in water, while alloy steels are hardened in oil. Non-ferrous metals are generally quenched in water. The first stage of heat treatment involves subjecting the material to controlled heating. The temperature and duration of heating are crucial factors that determine the final properties of the material. During this stage, the material is heated to a specific temperature, known as the austenitizing temperature, which varies depending on the type of material being treated. This temperature is carefully chosen to allow the material's microstructure to transform into a more desirable state. Once the material reaches the desired temperature, it is held at that temperature for a specific period, known as the soaking or holding time. This stage allows for the uniform distribution of heat throughout the material, ensuring that the desired transformations occur consistently. The soaking time is determined by factors such as the material's composition, size, and desired properties. It is during this stage that the material's microstructure undergoes significant changes, setting the foundation for the desired material properties. See also What is post weld heat treatment (PWHT) or stress relieving?After the soaking stage, the material is rapidly cooled to achieve the desired properties. The cooling rate is a critical parameter that determines the final microstructure and, consequently, the material's properties. Different cooling methods, such as air cooling, oil quenching, or water quenching, are employed depending on the material and the desired outcome. The cooling rate affects the formation of different phases within the material, such as martensite, bainite, or pearlite, which directly influence its hardness, strength, and toughness. In many cases, the material's properties after the cooling stage may not be ideal for the intended application. To alleviate this, the material undergoes a tempering stage. Tempering involves reheating the material to a specific temperature below its critical point and holding it at that temperature for a predetermined time. This process helps to relieve internal stresses, improve ductility, and enhance toughness while maintaining an acceptable level of hardness. The tempering temperature and time are carefully chosen to achieve the desired balance of properties. Depending on the specific requirements, additional treatments may be applied to further enhance the material's properties. These treatments can include processes like carburizing, nitriding, or annealing, which are designed to introduce specific elements or alter the microstructure to achieve desired characteristics such as increased surface hardness, wear resistance, or improved machinability. Ever wondered how metals become stronger, more flexible, or resistant to wear? The answer often lies in a process called heat treatment—a crucial step that transforms ordinary materials into powerhouses for everything from cookware to cars. Understanding how heat treatment works can help you select the right metals for your projects or ensure their long-lasting performance. In this article, you'll discover how the heat treatment process works, the main methods involved, and practical tips to get the best results. Related Video What is the Heat Treatment Process? Heat treatment is a critical industrial process where metals are heated and cooled under controlled conditions. The primary goal is to change the physical (and sometimes chemical) properties of the material—most often to make metals stronger, harder, or more ductile. This process is essential in industries like automotive, manufacturing, aerospace, and tool-making, where the right material properties can make a big difference. Simply put, heat treatment helps metals perform better in specific environments by tweaking their internal structure. How Does the Heat Treatment Process Work? The heat treatment process involves three main stages: 1. Heating The metal is heated to a specific temperature, sometimes quite high. The temperature is chosen based on the type of metal and the desired properties. Heating must be uniform to prevent stress or cracks. 2. Soaking (Holding) The metal is held at the target temperature for a certain amount of time. This allows the internal structure of the metal (grains and crystals) to transform. 3. Cooling The material is cooled under controlled conditions. Cooling can be slow (furnace cooling or air cooling) or fast (quenching in water or oil). The cooling rate strongly affects the final properties. Types of Heat Treatment Processes Different heat treatment methods are used depending on the desired outcome: 1. Annealing Softens metal, making it easier to work with. Increases ductility and reduces hardness. Involves slow heating and cooling. 2. Hardening Increases hardness and strength. Usually involves rapid cooling (quenching) after heating. 3. Tempering Performed after hardening to reduce brittleness. Heats the hardened metal to a lower temperature, then cools it in air. 4. Normalizing Used mainly for steels. Heats metal to a specific temperature, then cools it in air. Refines grain size and improves toughness. 5. Case Hardening Hardens only the surface (case) of the metal, leaving the core softer. Useful for gears and other parts requiring a hard exterior and tough interior. 6. Solution Treatment and Aging Often used for aluminum alloys. Dissolves alloying elements into solid solution during heating, then aging allows elements to precipitate and strengthen the metal. Detailed Steps in the Heat Treatment Process Here's a step-by-step breakdown of a typical heat treatment process: Selection of Material and Objective Define what you want from the metal (hardness, toughness, ductility). Choose the right alloy for the job. Preparation Clean the metal to remove oil, paint, or contaminants. Measure and plan for any changes in size due to heating. Heating Place metal in a furnace, torch, or induction heater. Slowly heat to prevent internal stresses. Monitor temperature precisely. Soaking Hold at the required temperature. Duration depends on the thickness and type of material. Cooling Cool according to the required method for the treatment: Air cooling (slow) Furnace cooling (very slow) Oil or water quenching (rapid) Brine or special salt baths (very rapid) Post-Treatment Check dimensions and shape (some distortion may occur). Conduct testing (hardness test, microscopic analysis). Perform additional finishing steps if necessary (grinding, polishing). Benefits of Heat Treatment Heat treatment brings a variety of benefits: Improved Mechanical Properties: Enhances hardness, strength, toughness, and ductility. Wear and Corrosion Resistance: Especially through surface hardening methods. Tailored Properties: Enables you to fine-tune materials for specific applications. Stress Relief: Removes internal stresses from prior manufacturing steps. Machinability Improvement: Makes metals easier to cut, form, or machine. Challenges and Considerations While heat treatment is invaluable, it's not without its challenges: Distortion and Cracking: Uneven heating or cooling can cause stress and even cracking. Cost of Equipment: Specialized furnaces and control systems can be expensive. Energy Consumption: The process can be energy-intensive, particularly for larger components. Control and Monitoring: Accurate temperature and timing control are essential for consistent results. Material Selection: Not all metals respond to every heat treatment equally. Practical Tips and Best Practices Getting the best out of your heat treatment process means following some tried-and-true advice: Clean Materials Thoroughly: Dirt or oil can impact the treatment outcome. Use Controlled Atmosphere: Protect metal from oxidation with inert gas or vacuum furnaces. Monitor Temperature and Time Precisely: Errors in either can result in sub-par properties. Allow for Size Changes: Metals may expand or contract; plan for this in production. Test Results Regularly: Don't skip post-treatment inspections. Choose the Correct Cooling Medium: Water is faster but harsher, oil is gentler, and air is the slowest. Document Your Process: Consistent record-keeping helps reproduce results and troubleshoot issues. Cost Tips for Heat Treatment If you are shipping parts to or from a heat treatment facility, or worried about the overall cost, keep these points in mind: Batch Processing: Treat multiple parts at once to save on per-item costs. Local Facilities: Minimize shipping distances to reduce transport costs and risk. Standard Sizes: Use standard-sized components to leverage existing furnace setups. Compare Quotes: Get multiple quotations for heat treatment services. Plan Ahead: Last-minute processing and shipping escalate costs. Quality Saves Money: Properly treated parts avoid expensive failures in service. Key Applications of Heat Treatment Heat treatment appears in many industries: Automotive: Strengthening gears, shafts, and engine components. Aerospace: Making critical parts stronger and more fatigue-resistant. Tool Manufacturing: Creating durable cutting tools and dies. Construction: Enhancing steel beams and reinforcements. Consumer Goods: Improving cutlery, springs, and kitchenware. Summary The heat treatment process is a cornerstone of modern metallurgy and engineering. By carefully heating and cooling metals, you can tailor materials to fit a vast array of applications. Mastering the different processes—like annealing, hardening, tempering, and case hardening—unlocks potential in products ranging from automotive gears to aerospace components. Regardless of your level of experience, paying close attention to preparation, precise control, and post-treatment testing ensures the best results. Remember, a well-treated component is a foundation for safe, reliable, and long-lasting products. Frequently Asked Questions (FAQs) What is the main purpose of heat treating metal? The main purpose is to improve the metal's physical properties, such as hardness, strength, ductility, or toughness, making it more suitable for its intended application. Can all metals be heat treated? Most metals can be heat treated, but the results depend on the metal's composition. Ferrous metals (like steel and iron) respond best, while some non-ferrous metals and alloys require specialized processes. What is quenching, and why is it important? Quenching is the rapid cooling of heated metal, typically in water, oil, or air. It locks certain structural changes in place, increasing hardness and strength, but may also increase brittleness. How do I know which heat treatment process to use? The right process depends on your desired end properties and the specific metal involved. Consult with material specialists or refer to manufacturer guidelines to select the most appropriate treatment. Does heat treatment change the appearance of metal? Heat treatment can affect surface color (such as tempering colors), cause slight distortion, or even lead to scaling if not protected, but the main changes are internal, not cosmetic. Process of heating something to alter it Heat treating furnace at 1,800 °F (980 °C) Heat treating (or heat treatment) is a group of industrial, thermal and metalworking processes used to alter the physical, and sometimes chemical, properties of a material. The most common application is metallurgical. Heat treatments are also used in the manufacture of many other materials, such as glass. Heat treatment involves the use of heating or chilling, normally to extreme temperatures, to achieve the desired result such as hardening or softening of a material. Heat treatment techniques include annealing, case hardening, precipitation strengthening, tempering, carburizing, normalizing and quenching. Although the term heat treatment applies only to processes where the heating and cooling are done for the specific purpose of altering properties intentionally, heating and cooling often occur incidentally during other manufacturing processes such as hot forming or welding. Allotropes of iron, showing the differences in lattice structures between alpha iron (low temperature) and gamma iron (high temperature). The alpha iron has no spaces for carbon atoms to reside, while the gamma iron is open to the free movement of small carbon atoms. Photomicrographs of steel. Top: In annealed (slowly cooled) steel, the carbon precipitates forming layers of ferrite (iron) and cementite (carbide). Bottom: In quenched (quickly cooled) steel, the carbon remains trapped in the iron, creating great internal stresses in the needle or plate-like grains. Metallic materials consist of a microstructure of small crystals called "grains" or crystallites. The nature of the grains (i.e. grain size and composition) is one of the most effective factors that can determine the overall mechanical behavior of the metal. Heat treatment provides an efficient way to manipulate the properties of the metal by controlling the rate of diffusion and the rate of cooling within the microstructure. Heat treating is often used to alter the mechanical properties of a metallic alloy, manipulating properties such as the hardness, strength, toughness, ductility, and elasticity.[1] There are two mechanisms that may change an alloy's properties during heat treatment: the formation of martensite causes the crystals to deform intrinsically, and the diffusion mechanism causes changes in the homogeneity of the alloy.[2] The crystal structure consists of atoms that are grouped in a very specific arrangement, called a lattice. In most elements, this order will rearrange itself, depending on conditions like temperature and pressure. This rearrangement called allotropy or polymorphism, may occur several times, at many different temperatures for a particular metal. In alloys, this rearrangement may cause an element that will not normally dissolve into the base metal to suddenly become soluble, while a reversal of the allotropy will make the elements either partially or completely insoluble.[3] When in the soluble state, the process of diffusion causes the atoms of the dissolved element to spread out, attempting to form a homogenous distribution within the crystals of the base metal. If the alloy is cooled to an insoluble state, the atoms of the dissolved constituents (solutes) may migrate out of the solution. This type of diffusion, called precipitation, leads to nucleation, where the migrating atoms group together at the grain-boundaries. This forms a microstructure generally consisting of two or more distinct phases.[4] For instance, steel that has been heated above the austenizing temperature (red to orange-hot, or around 1,500 °F (820 °C) to 1,600 °F (870 °C) depending on carbon content), and then cooled slowly, forms a laminated structure composed of alternating layers of ferrite and cementite, becoming soft pearlite.[5] After heating the steel to the austenite phase and then quenching it in water, the microstructure will be in the martensitic phase. This is due to the fact that the steel will change from the austenite phase to the martensite phase after quenching. Some pearlite or ferrite may be present if the quench did not rapidly cool off all the steel.[4] Unlike iron-based alloys, most heat-treatable alloys do not experience a ferrite transformation. In these alloys, the nucleation at the grain-boundaries often reinforces the structure of the crystal matrix. These metals harden by precipitation. Typically a slow process, depending on temperature, this is often referred to as "age hardening".[6] Many metals and non-metals exhibit a martensite transformation when cooled quickly (with external media like oil, polymer, water, etc.). When a metal is cooled very quickly, the insoluble atoms may not be able to migrate out of the solution in time. This is called a "diffusionless transformation." When the crystal matrix changes to its low-temperature arrangement, the atoms of the solute become trapped within the lattice. The trapped atoms prevent the crystal matrix from completely changing into its low-temperature allotrope, creating shearing stresses within the lattice. When some alloys are cooled quickly, such as steel, the martensite transformation hardens the metal, while in others, like aluminum, the alloy becomes softer.[7][8] Phase diagram of an iron-carbon alloying system. Phase changes occur at different temperatures (vertical axis) for different compositions (horizontal axis). The dotted lines mark the eutectoid (A) and eutectic (B) compositions.The specific composition of an alloy system will usually have a great effect on the results of heat treating. If the percentage of each constituent is just right, the alloy will form a single, continuous microstructure upon cooling. Such a mixture is said to be eutectoid. However, If the percentage of the solutes varies from the eutectoid mixture, two or more different microstructures will usually form simultaneously. A hypo eutectoid solution contains less of the solute than the eutectoid mix, while a hypereutectoid solution contains more.[9] A eutectoid (eutectic-like) alloy is similar in behavior to a eutectic alloy. A eutectic alloy is characterized by having a single melting point. This melting point is lower than that of any of the constituents, and no change in the mixture will lower the melting point any further. When a molten eutectic alloy is cooled, all of the constituents will crystallize into their respective phases at the same temperature. A eutectoid alloy is similar, but the phase change occurs, not from a liquid, but from a solid solution. Upon cooling a eutectoid alloy from the solution temperature, the constituents will separate into different crystal phases, forming a single microstructure. A eutectoid steel, for example, contains 0.77% carbon. Upon cooling slowly, the solution of iron and carbon (a single phase called austenite) will separate into platelets of the phases ferrite and cementite. This forms a layered microstructure called pearlite. Since pearlite is harder than iron, the degree of softness achievable is typically limited to that produced by the pearlite. Similarly, the hardenability is limited by the continuous martensitic microstructure formed when cooled very fast.[10] A hypoeutectic alloy has two separate melting points. Both are above the eutectic melting point for the system but are below the melting points of any constituent forming the system. Between these two melting points, the alloy will exist as part solid and part liquid. The constituent with the higher melting point will solidify first. When completely solidified, a hypoeutectic alloy will often be in a solid solution. Similarly, a hypoeutectoid alloy has two critical temperatures, called "arrests". Between these two temperatures, the alloy will exist partly as the solution and partly as a separate crystallizing phase, called the "pro eutectoid phase". These two temperatures are called the upper (A3) and lower (A1) transformation temperatures. As the solution cools from the upper transformation temperature toward an insoluble state, the excess base metal will often be forced to "crystallize-out", becoming the pro eutectoid. This will occur until the remaining concentration of solutes reaches the eutectoid level, which will then crystallize as a separate microstructure. For example, a hypoeutectoid steel contains less than 0.77% carbon. Upon cooling a hypoeutectoid steel from the austenite transformation temperature, small islands of proeutectoid-ferrite will form. These will continue to grow and the carbon will recede until the eutectoid concentration in the rest of the steel is reached. This eutectoid mixture will then crystallize as a microstructure of pearlite. Since ferrite is softer than pearlite, the two microstructures combine to increase the ductility of the alloy. Consequently, the hardenability of the alloy is lowered.[11] Hypereutectoid steel A hypereutectic alloy also has different melting points. However, between these points, it is the constituent with the higher melting point that will be solid. Similarly, a hypereutectoid alloy has two critical temperatures. When cooling a hypereutectoid alloy from the upper transformation temperature, it will usually be the excess solutes that crystallize-out first, forming the pro-eutectoid. This continues until the concentration in the remaining alloy becomes eutectoid, which then crystallizes into a separate microstructure. A hypereutectoid steel contains more than 0.77% carbon. When slowly cooling hypereutectoid steel, the cementite will begin to crystallize first. When the remaining steel becomes eutectoid in composition, it will crystallize into pearlite. Since cementite is much harder than pearlite, the alloy has greater hardenability at a cost in ductility.[9][11] Time-temperature transformation (TTT) diagram for steel. The red curves represent different cooling rates (velocity) when cooled from the upper critical (A3) temperature. V1 (quenching) produces martensite. V2 (normalizing) produces both pearlite and martensite, V3 (annealing) produces bainite mixed with pearlite. Proper heat treating requires precise control over temperature, time held at a certain temperature and cooling rate.[12] With the exception of stress-relieving, tempering, and aging, most heat treatments begin by heating an alloy beyond a certain transformation, or arrest (A), temperature. This temperature is referred to as an "arrest" because at the A temperature the metal experiences a period of hysteresis. At this point, all of the heat energy is used to cause the crystal change, so the temperature stops rising for a short time (arrests) and then continues climbing once the change is complete.[13] Therefore, the alloy must be heated above the critical temperature for a transformation to occur. The alloy will usually be held at this temperature long enough for the heat to completely penetrate the alloy, thereby bringing it into a complete solid solution. Iron, for example, has four critical-temperatures, depending on carbon content. Pure iron in its alpha (room temperature) state changes to nonmagnetic gamma-iron at its A2 temperature, and weldable delta-iron at its A4 temperature. However, as carbon is added, becoming steel, the A2 temperature splits into the A3 temperature, also called the austenizing temperature (all phases become austenite, a solution of gamma iron and carbon) and its A1 temperature (austenite changes into pearlite upon cooling). Between these upper and lower temperatures the pro eutectoid phase forms upon cooling. Because a smaller grain size usually enhances mechanical properties, such as toughness, shear strength and tensile strength, these metals are often heated to a temperature that is just above the upper critical temperature, in order to prevent the grains of solution from growing too large. For instance, when steel is heated above the upper critical-temperature, small grains of austenite form. These grow larger as the temperature is increased. When cooled very quickly, during a martensite transformation, the austenite grain-size directly affects the martensitic grain-size. Larger grains have large grain-boundaries, which serve as weak spots in the structure. The grain size is usually controlled to reduce the probability of breakage.[14] The diffusion transformation is very time-dependent. Cooling a metal will usually suppress the precipitation to a much lower temperature. Austenite, for example, usually only exists above the upper critical temperature. However, if the austenite is cooled quickly enough, the transformation may be suppressed for hundreds of degrees below the lower critical temperature. Such austenite is highly unstable and, if given enough time, will precipitate into various microstructures of ferrite and cementite. The cooling rate can be used to control the rate of grain growth or can even be used to produce partially martensitic microstructures.[15] However, the martensite transformation is time-independent. If the alloy is cooled to the martensite transformation (Ms) temperature before other microstructures can fully form, the transformation will usually occur at just under the speed of sound.[16] When austenite is cooled but kept above the martensite start temperature Ms so that a martensite transformation does not occur, the austenite grain size will have an effect on the rate of nucleation, but it is generally temperature and the rate of cooling that controls the grain size and microstructure. When austenite is cooled extremely slowly, it will form large ferrite crystals filled with spherical inclusions of cementite. This microstructure is referred to as "sphereoidite". If cooled a little faster, then coarse pearlite will form. Even faster, and fine pearlite will form. If cooled even faster, bainite will form, with more complete bainite transformation occurring depending on the time held above martensite start Ms. Similarly, these microstructures will also form, if cooled to a specific temperature and then held there for a certain time.[17] Most non-ferrous alloys are also heated in order to form a solution. Most often, these are then cooled very quickly to produce a martensite transformation, putting the solution into a supersaturated state. The alloy, being in a much softer state, may then be cold worked. This causes work hardening that increases the strength and hardness of the alloy. Moreover, the defects caused by plastic deformation tend to speed up precipitation, increasing the hardness beyond what is normal for the alloy. Even if not cold worked, the solutes in these alloys will usually precipitate, although the process may take much longer. Sometimes these metals are then heated to a temperature that is below the lower critical (A1) temperature, preventing recrystallization, in order to speed-up the precipitation.[18][19][20] Steel castings after undergoing 12-hour 1,200 °C (2,190 °F) heat treatment. Complex heat treating schedules, or "cycles", are often devised by metallurgists to optimize an alloy's mechanical properties. In the aerospace industry, a superalloy may undergo five or more different heat treating operations to develop the desired properties. [citation needed] This can lead to quality problems depending on the accuracy of the furnace's temperature controls and timer. These operations can usually be divided into several basic techniques. Main article: Annealing (metallurgy) Annealing consists of heating a metal to a specific temperature and then cooling at a rate that will produce a refined microstructure, either fully or partially separating the constituents. The rate of cooling is generally slow. Annealing is most often used to soften a metal for cold working, to improve machinability, or to enhance properties like electrical conductivity. In ferrous alloys, annealing is usually accomplished by heating the metal beyond the upper critical temperature and then cooling very slowly, resulting in the formation of pearlite. In both pure metals and many alloys that cannot be heat treated, annealing is used to remove the hardness caused by cold working. The metal is heated to a temperature where recrystallization can occur, thereby repairing the defects caused by plastic deformation. In these metals, the rate of cooling will usually have little effect. Most non-ferrous alloys that are heat-treatable are also annealed to relieve the hardness of cold working. These may be slowly cooled to allow full precipitation of the constituents and produce a refined microstructure. Ferrous alloys are usually either "full annealed" or "process annealed". Full annealing requires very slow cooling rates, in order to form coarse pearlite. In process annealing, the cooling rate may be faster; up to, and including normalizing. The main goal of process annealing is to produce a uniform microstructure. Non-ferrous alloys are often subjected to a variety of annealing techniques, including "recrystallization annealing", "partial annealing", "full annealing", and "final annealing". Not all annealing techniques involve recrystallization, such as stress relieving.[21] Normalizing is a technique used to provide uniformity in grain size and composition (equiaxed crystals) throughout an alloy. The term is often used for ferrous alloys that have been austenitized and then cooled in the open air.[21] Normalizing not only produces pearlite but also martensite and sometimes bainite, which gives harder and stronger steel but with less ductility for the same composition than full annealing. In the normalizing process the steel is heated to about 40 degrees Celsius above its upper critical temperature limit, held at this temperature for some time, and then cooled in air. Stress-relieving is a technique to remove or reduce the internal stresses created in metal. These stresses may be caused in a number of ways, ranging from cold working to non-uniform cooling. Stress-relieving is usually accomplished by heating a metal below the lower critical temperature and then cooling uniformly.[21] Stress relieving is commonly used on items like air tanks, boilers and other pressure vessels, to remove a portion of the stresses created during the welding process.[22] Main article: Precipitation hardening Some metals are classified as precipitation hardening metals. When a precipitation hardening alloy is quenched, its alloying elements will be trapped in solution, resulting in a soft metal. Aging a "solutionized" metal will allow the alloying elements to diffuse through the microstructure and form intermetallic particles. These intermetallic particles will nucleate and fall out of the solution and act as a reinforcing phase, thereby increasing the strength of the alloy. Alloys may age " naturally" meaning that the precipitates form at room temperature, or they may age "artificially" when precipitates only form at elevated temperatures. In some applications, naturally aging alloys may be stored in a freezer to prevent hardening until after further operations - assembly of rivets, for example, maybe easier with a softer part. Examples of precipitation hardening alloys include 2000 series, 6000 series, and 7000 series aluminium alloy, as well as some superalloys and some stainless steels. Steels that harden by aging are typically referred to as maraging steels, from a combination of the term "martensite aging".[21] Main article: Quenching Quenching is a process of cooling a metal at a rapid rate. This is most often done to produce a martensite transformation. In ferrous alloys, this will often produce a harder metal, while non-ferrous alloys will usually become softer than normal. To harden by quenching, a metal (usually steel or cast iron) must be heated above the upper critical temperature (Steel: above 815~900 degrees Celsius[23]) and then quickly cooled. Depending on the alloy and other considerations (such as concern for maximum hardness vs. cracking and distortion), cooling may be done with forced air or other gases, (such as nitrogen). Liquids may be used, due to their better thermal conductivity, such as oil, water, a polymer dissolved in water, or a brine. Upon being rapidly cooled, a portion of austenite (dependent on alloy composition) will transform to martensite, a hard, brittle crystalline structure. The quenched hardness of a metal depends on its chemical composition and quenching method. Cooling speeds, from fastest to slowest, go from brine, polymer (i.e. mixtures of water + glycol polymers), freshwater, oil, and forced air. However, quenching certain steel too fast can result in cracking, which is why high-tensile steels such as AISI 4140 should be quenched in oil, tool steels such as ISO 1.2767 or H13 hot work tool steel should be quenched in forced air, and low alloy or medium-tensile steels such as XK1320 or AISI 1040 should be quenched in brine. Some Beta titanium based alloys have also shown similar trends of increased strength through rapid cooling.[24] However, most non-ferrous metals, like alloys of copper, aluminum, or nickel, and some high alloy steels such as austenitic stainless steel (304, 316), produce an opposite effect when these are quenched: they soften. Austenitic stainless steels must be quenched to become fully corrosion resistant, as they work-harden significantly.[21] Main article: Tempering (metallurgy) Untempered martensitic steel, while very hard, is too brittle to be useful for most applications. A method for alleviating this problem is called tempering. Most applications require that quenched parts be tempered. Tempering consists of heating steel below the lower critical temperature, (often from 400˚F to 1105˚F or 205˚C to 595˚C, depending on the desired results), to impart some toughness. Higher tempering temperatures (maybe up to 1,300˚F or 700˚C, depending on the alloy and application) are sometimes used to impart further ductility, although some yield strength is lost. Tempering may also be performed on normalized steels. Other methods of tempering consist of quenching to a specific temperature, which is above the martensite start temperature, and then holding it there until pure bainite can form or internal stresses can be relieved. These include austempering and martempering.[21] Tempering colors of steel Steel that has been freshly ground or polished will form oxide layers when heated. At a very specific temperature, the iron oxide will form a layer with a very specific thickness, causing thin-film interference. This causes colors to appear on the surface of the steel. As the temperature is increased, the iron oxide layer grows in thickness, changing the color.[25] These colors, called tempering colors, have been used for centuries to gauge the temperature of the metal.[26] 350˚F (176˚C), light yellowish 400˚F (204˚C), light-straw 440˚F (226˚C), dark-straw 500˚F (260˚C), brown 540˚F (282˚C), purple 590˚F (310˚C), deep blue 640˚F (337˚C), light blue[26] The tempering colors can be used to judge the final properties of the tempered steel. Very hard tools are often tempered in the light to the dark straw range, whereas springs are often tempered to the blue. However, the final hardness of the tempered steel will vary, depending on the composition of the steel. Higher-carbon tool steel will remain much harder after tempering than spring steel (of slightly less carbon) when tempered at the same temperature. The oxide film will also increase in thickness over time. Therefore, steel that has been held at 400˚F for a very long time may turn brown or purple, even though the temperature never exceeded that needed to produce a light straw color. Other factors affecting the final outcome are oil films on the surface and the type of heat source used.[26] Main article: Differential heat treatment Many heat treating methods have been developed to alter the properties of only a portion of an object. These tend to consist of either cooling different areas of an alloy at different rates, by quickly heating in a localized area and then quenching, by thermochemical diffusion, or by tempering different areas of an object at different temperatures, such as in differential tempering. [citation needed] Main article: Differential hardening A differentially hardened katana. The bright, wavy line following the hamon, called the nioi, separates the martensitic edge from the pearlitic back. The inset shows a close-up of the nioi, which is made up of individual martensite grains (niye) surrounded by pearlite. The wood-grain appearance comes from layers of different compositions.Some techniques allow different areas of a single object to receive different heat treatments. This is called differential hardening. It is common in high quality knives and swords. The Chinese jian is one of the earliest known examples of this, and the Japanese katana may be the most widely known. The Nepalese Khukuri is another example. This technique uses an insulating layer, like layers of clay, to cover the areas that are to remain soft. The areas to be hardened are left exposed, allowing only certain parts of the steel to fully harden when quenched. [citation needed] Main article: Surface hardening Flame hardening is used to harden only a portion of a metal. Unlike differential hardening, where the entire piece is heated and then cooled at different rates, in flame hardening, only a portion of the metal is heated before quenching. This is usually easier than differential hardening, but often produces an extremely brittle zone between the heated metal and the unheated metal, as cooling at the edge of this heat-affected zone is extremely rapid. [citation needed] Main article: Induction hardening Induction hardening is a surface hardening technique in which the surface of the metal is heated very quickly, using a no-contact method of induction heating. The alloy is then quenched, producing a martensite transformation at the surface while leaving the underlying metal unchanged. This creates a very hard, wear-resistant surface while maintaining the proper toughness in the majority of the object. Crankshaft journals are a good example of an induction hardened surface.[27] Main article: Case hardening Case hardening is a thermochemical diffusion process in which an alloying element, most commonly carbon or nitrogen, diffuses into the surface of a monolithic metal. The resulting interstitial solid solution is harder than the base material, which improves wear resistance without sacrificing toughness.[21] Laser surface engineering is a surface treatment with high versatility, selectivity and novel properties. Since the cooling rate is very high in laser treatment, metastable even metallic glass can be obtained by this method. Main article: Cryogenic treatment Although quenching steel causes the austenite to transform into martensite, all of the austenite usually does not transform. Some austenite crystals will remain unchanged even after quenching below the martensite finish (Mf) temperature. Further transformation of the austenite into martensite can be induced by slowly cooling the metal to extremely low temperatures. Cold treating generally consists of cooling the steel to around -115˚F (-81˚C), but does not eliminate all of the austenite. Cryogenic treating usually consists of cooling to much lower temperatures, often in the range of -315˚F (-192˚C), to transform most of the austenite into martensite. Cold and cryogenic treatments are typically done immediately after quenching, before any tempering, and will increase the hardness, wear resistance, and reduce the internal stresses in the metal but, because it is really an extension of the quenching process, it may increase the chances of cracking during the procedure. The process is often used for tools, bearings, or other items that require good wear resistance. However, it is usually only effective in high-carbon or high-alloy steels in which more than 10% austenite is retained after quenching.[28][29] The heating of steel is sometimes used as a method to alter the carbon content. When steel is heated in an oxidizing environment, the oxygen combines with the iron to form an iron-oxide layer, which protects the steel from decarburization. When the steel turns to austenite, however, the oxygen combines with iron to form a slag, which provides no protection from decarburization. The formation of slag and scale actually increases decarburization, because the iron oxide keeps oxygen in contact with the decarburization zone even after the steel is moved into an oxygen-free environment, such as the coals of a forge. Thus, the carbon atoms begin combining with the surrounding scale and slag to form both carbon monoxide and carbon dioxide, which is released into the air. Steel contains a relatively small percentage of carbon, which can migrate freely within the gamma iron. When austenitized steel is exposed to air for long periods of time, the carbon content in the steel can be lowered. This is the opposite from what happens when steel is heated in a reducing environment, in which carbon slowly diffuses further into the metal. In an oxidizing environment, the carbon can readily diffuse outwardly, so austenitized steel is very susceptible to decarburization. This is often used for cast steel, where a high carbon-content is needed for casting, but a lower carbon-content is desired in the finished product. It is often used on cast-irons to produce malleable cast iron, in a process called "white tempering". This tendency to decarburize is often a problem in other operations, such as blacksmithing, where it becomes more desirable to austenize the steel for the shortest amount of time possible to prevent too much decarburization.[30] Usually the end condition is specified instead of the process used in heat treatment.[31] A modern, fully computerised case hardening furnace. Case hardening is specified by "hardness" and "case depth". The case depth can be specified in two ways: total case depth or effective case depth. The total case depth is the true depth of the case. For most alloys, the effective case depth is the depth of the case that has a hardness equivalent of HRC50; however, some alloys specify a different hardness (40-60 HRC) at effective case depth; this is checked on a Tukon microhardness tester. This value can be roughly approximated as 65% of the total case depth; however, the chemical composition and hardenability can affect this approximation. If neither type of case depth is specified the total case depth is assumed.[31] For case hardened parts the specification should have a tolerance of at least ±0.005 in (0.13 mm). If the part is to be ground after heat treatment, the case depth is assumed to be after grinding.[31] The Rockwell hardness scale used for the specification depends on the depth of the total case depth, as shown in the table below. Usually, hardness is measured on the Rockwell "C" scale, but the load used on the scale will penetrate through the case if the case is less than 0.030 in (0.76 mm). Using Rockwell "C" for a thinner case will result in a false reading.[31] Rockwell scale required for various case depths[31] Total case depth, min. [in] Rockwell scale 0.030 C 0.024 A 0.021 45 N 0.018 30 N 0.015 15 N Less than 0.015 "File hard" For cases that are less than 0.015 in (0.38 mm) thick a Rockwell scale cannot reliably be used, so file hard is specified instead.[31] File hard is approximately equivalent to 58 HRC.[32] When specifying the hardness either a range should be given or the minimum hardness specified. If a range is specified at least 5 points should be given.[31] Only hardness is listed for through hardening. It is usually in the form of HRC with at least a five-point range.[31] The hardness for an annealing process is usually listed on the HRB scale as a maximum value.[31] It is a process to refine grain size, improve strength, remove residual stress, and affect the electromagnetic properties... Furnaces used for heat treatment can be split into two broad categories: batch furnaces and continuous furnaces. Batch furnaces are usually manually loaded and unloaded, whereas continuous furnaces have an automatic conveying system to provide a constant load into the furnace chamber.[33] Batch systems usually consist of an insulated chamber with a steel shell, a heating system, and an access door to the chamber.[33] Many basic box-type furnaces have been upgraded to a semi-continuous batch furnace with the addition of integrated quench tanks and slow-cool chambers. These upgraded furnaces are a very commonly used piece of equipment for heat-treating.[33] Also known as a " bogie hearth", the car furnace is an extremely large batch furnace. The floor is constructed as an insulated movable car that is moved in and out of the furnace for loading and unloading. The car is usually sealed using sand seals or solid seals when in position. Due to the difficulty in getting a sufficient seal, car furnaces are usually used for non-atmosphere processes. [citation needed] Fluidised bed heat treatment line Similar in type to the car furnace, except that the car and hearth are rolled into position beneath the furnace and raised by means of a motor-driven mechanism, elevator furnaces can handle large heavy loads and often eliminate the need for any external cranes and transfer mechanisms.[33] Bell furnaces have removable covers called bells, which are lowered over the load and hearth by crane. An inner bell is placed over the hearth and sealed to supply a protective atmosphere. An outer bell is lowered to provide the heat supply.[33] Furnaces that are constructed in a pit and extend to floor level or slightly above are called pit furnaces. Workpieces can be suspended from fixtures, held in baskets, or placed on bases in the furnace. Pit furnaces are suited to heating long tubes, shafts, and rods by holding them in a vertical position. This manner of loading provides minimal distortion.[33] Salt baths are used in a wide variety of heat treatment processes including neutral hardening, liquid carburising, liquid nitriding, austempering, martempering and tempering. Parts are loaded into a pot of molten salt where they are heated by conduction, giving a very readily available source of heat. The core temperature of a part rises in temperature at approximately the same rate as its surface in a salt bath.[33] Salt baths utilize a variety of salts for heat treatment, with cyanide salts being the most extensively used. Concerns about associated occupation health and safety, and expensive waste management and disposal due to their environmental effects have made the use of salt baths less attractive in recent years. Consequently, many salt baths are being replaced by more environmentally friendly fluidized bed furnaces.[34] A fluidised bed consists of a cylindrical retort made from high-temperature alloy, filled with sand-like aluminum oxide particulate. Gas (air or nitrogen) is bubbled through the oxide and the sand moves in such a way that it exhibits fluid-like behavior, hence the term fluidized. The solid-solid contact of the oxide gives very high thermal conductivity and excellent temperature uniformity throughout the furnace, comparable to those seen in a salt bath.[33] Carbon steel Carbonizing Diffusion hardening Induction hardening Retrogression heat treatment Nitriding ^ ZIA, Abdul Wasy; Zhou, Zhifeng; Po-wan, Shum.; Lawrence Li, Kwak Yan (24 January 2017). "The effect of two-step heat treatment on hardness, fracture toughness, and wear of different biased diamond-like carbon coatings". Surface and Coatings Technology. 320: 118–125. doi:10.1016/j.surfcoat.2017.01.089. ^ Shant P. Gupta (2002). Solid state phase transformations. Allied Publishers Private Limited. pp. 28–29. ^ Robert W. Cahn; Peter Haasen, eds. (1996). Physical Metallurgy. Vol. 2. Elsevier Science. pp. 10–11. ^ a b Alvarenga, H. D.; Van de Putte, T.; Van Steenberge, N.; Sietsma, J.; Terryn, H. (8 October 2014). "Influence of Carbide Morphology and Microstructure on the Kinetics of Superficial Decarburization of C-Mn Steels". Metallurgical and Materials Transactions A. 46: 123–133. doi:10.1007/s11661-014-2600-y. S2CID 136871961. ^ Physical Metallurgy 1996, pp. 136–198 ^ Gupta 2002, pp. 299–347 ^ Physical Metallurgy 1996, pp. 1508–1543 ^ Gupta 2002, pp. 501–518 ^ a b B.B. Patra; Biswajit Samantray (2011). Engineering Chemistry I. Dorling Kindersley. pp. 75–77. ^ Dossett, Jon L.; Boyer, Howard E. (2006). Practical heat treating. ASM International. pp. 17–22. ^ a b Dossett & Boyer 2006, pp. 17–22 ^ Rajan, T. V.; Sharma, C. P.; Sharma, Ashok (1992). Heat Treatment: Principles and Techniques. Prentence Hall. p. 1. ^ New Edge of the Anvil: A Resource Book for the Blacksmith by Jack Andrews --Shipjack Press 1994 Page 93--96 ^ Rajan & Sharma 1992, pp. 62–67 ^ Dossett & Boyer 2006, pp. 23–25 ^ The physics of phase transitions: concepts and applications By Pierre Papon, Jacques Leblond, Paul Herman Ernst Meijer - Springer-Verlag Berlin Heidelberg 2006 Page 66 ^ Rajan & Sharma 1992 ^ Dossett & Boyer 2006, p. 231 ^ Rajan & Sharma 1992, pp. 187–190, 321 ^ Manufacturing technology: foundry, forming and welding By Rao - Tata McGraw-Hill 1998 Page 55 ^ a b c d e f g Dossett & Boyer 2006, pp. 2–6 ^ "The National Board of Boiler and Pressure Vessel Inspectors". www.nationalboard.org. Archived from the original on 20 December 2010. Retrieved 29 April 2018. ^ Aviation Maintenance Technician Handbook (FAA-H-8983-30A ed.). Federal Aviation Administration. 2018. ^ Najdahmadi, A.; Zarei-Hanzaki, A.; Farghadani, E. (1 February 2014). "Mechanical properties enhancement in Ti–29Nb–13Ta–4.6Zr alloy via heat treatment with no detrimental effect on its biocompatibility". Materials & Design. 54: 786–791. doi:10.1016/j.matdes.2013.09.007. ISSN 0261-3069. ^ Light, its interaction with art and antiquities By Thomas B. Brill - Plenum Publishing 1980 Page 55 ^ a b c Andrews, Jack (1994). New Edge of the Anvil: a resource book for the blacksmith. pp. 98–99. ^ Surface hardening of steels: understanding the basics By Joseph R. Davis - ASM International 2002 ^ Heat treater's guide: practices and procedures for irons and steels By ASM International - ASM International 2007 Page 12-13 ^ Handbook of residual stress and deformation of steel by George E. Totten, Maurice A. H. Howes, Tatsuo Inoue - ASM International 2002 Page 331-337 ^ Steel Heat Treatment: Metallurgy and Technologies By George E. Totten -- CRC press 2007 Page 306--308 ^ a b c d e f g h i "PMPA's Designer's Guide: Heat treatment". Archived from the original on 2009-07-14. Retrieved 2009-06-19. ^ Phone interview with the quality control inspector for FPM, Elk Grove Village, IL. 06-21-2010 ^ a b c d e f g h ASM International Handbook Committee. (1991). ASM Handbook, Volume 04 - Heat Treating. ASM International. ^ "Made in the Midlands | Fluidised beds: A Green Alternative to Salt Baths". claytonholdings.madeinthemidlands.com. Archived from the original on 2016-02-07. Retrieved 2015-06-02. International Heat Treatment Magazine in English Reed-Hill, Robert (1994). Principles of Physical Metallurgy (3rd ed.). Boston: PWS Publishing. Wikimedia Commons has media related to Heat treatment. Retrieved from " In the world of manufacturing and engineering, the heat treatment process plays a crucial role in enhancing the mechanical properties of various materials. From improving hardness and strength to increasing durability and resistance, heat treatment is a versatile technique that has been employed for centuries. In this article, we will delve into the fundamentals of the heat treatment process, exploring its different methods and the benefits it offers. Heat treatment is a controlled process that involves the heating and cooling of materials to alter their physical and mechanical properties. It is commonly used to modify the microstructure of metals and alloys, resulting in improved hardness, ductility, toughness, and other desirable characteristics. By subjecting materials to specific temperature ranges and cooling rates, heat treatment can significantly enhance their performance and suitability for various applications. The scientific principle behind heat treatment lies in the transformation of a material's microstructure, which directly affects its mechanical properties. By subjecting a material to specific temperatures and cooling rates, the arrangement of atoms within the material can be altered, leading to changes in its properties. Phase Transformation: During heat treatment, materials undergo phase transformations, which involve changes in the arrangement of atoms. These transformations occur at specific temperatures known as critical points. For example, during annealing, the material is heated to a temperature above its critical point, allowing the atoms to rearrange and form a more uniform and stable microstructure. Diffusion: Diffusion is a key physical process that occurs during heat treatment. It involves the movement of atoms within a material, allowing for the redistribution of elements and the formation of new phases. Diffusion is crucial for achieving desired material properties, such as increased hardness or improved corrosion resistance. Recrystallization: Recrystallization is a phenomenon that occurs during heat treatment, particularly during annealing. When a material is heated to a specific temperature, new grains with a more regular and uniform structure form, replacing the deformed grains present in the material. This process helps relieve internal stresses and improves the material's ductility and toughness. Martensitic Transformation: During the hardening process, rapid cooling (quenching) is employed to achieve high hardness. This rapid cooling rate suppresses the formation of equilibrium phases, resulting in the formation of a metastable phase called martensite. Martensite is characterized by a highly distorted atomic arrangement, which contributes to the material's increased hardness. Tempering: Tempering is a heat treatment step that follows hardening. It involves reheating the hardened material to a specific temperature and then cooling it down. This process allows for the transformation of some of the martensite into more stable phases, reducing the material's brittleness and improving its toughness and ductility. See also Heat Treatment Stages: Achieving Optimal Metal PropertiesOverall, the heat treatment process relies on the scientific understanding of phase transformations, diffusion, recrystallization, and the manipulation of material microstructures. By carefully controlling the heating and cooling parameters, manufacturers can achieve desired material properties, enhancing the mechanical characteristics and performance of the material for various applications. Presently, there are four fundamental categories of heat treatment methods that are widely employed. These include annealing, normalizing, hardening, and tempering. Annealing is a heat treatment method that involves heating a material to a specific temperature and then slowly cooling it down. This process helps relieve internal stresses, improve ductility, and refine the grain structure of the material. Annealing is commonly used to soften metals, making them easier to machine or shape. Quenching is a rapid cooling process that involves immersing a heated material into a liquid, typically oil or water. This sudden cooling rate helps achieve high hardness and strength by transforming the material's microstructure. Quenching is commonly used for hardening steel, creating a hardened surface layer while maintaining a tough core. See also Carburizing Heat Treatment Process Tempering is a heat treatment process that follows quenching. It involves reheating the quenched material to a specific temperature and then cooling it down. Tempering reduces the brittleness caused by quenching and improves toughness and ductility. The resulting material exhibits a balance between hardness and toughness, making it suitable for various applications. Case hardening is a heat treatment method used to increase the hardness of the surface layer of a material while maintaining a relatively softer core. This process involves introducing carbon or nitrogen into the material's surface through diffusion. Case hardening is commonly used in applications where wear resistance and surface hardness are critical, such as gears, bearings, and tools. The main advantages of Heat Treatment are: Improved hardness Increased strength Enhanced toughness Enhanced wear resistance Improved machinability Increased durability Reduced brittleness Enhanced corrosion resistance Tailored material properties Improved dimensional stability Improved Mechanical Properties: Heat treatment allows manufacturers to tailor the mechanical properties of materials to meet specific requirements. By altering the microstructure, heat treatment can enhance hardness, strength, toughness, and wear resistance, making materials more suitable for demanding applications. Increased Durability: Heat-treated materials exhibit improved resistance to wear, fatigue, and deformation. This increased durability extends the lifespan of components and reduces the need for frequent replacements, resulting in cost savings and improved reliability. Enhanced Machinability: Annealing, a common heat treatment method, softens materials, making them easier to machine or shape. This improves the efficiency of manufacturing processes and reduces tool wear, ultimately leading to cost savings. Tailored Material Performance: Different heat treatment methods can be combined or applied selectively to achieve specific material properties. This flexibility allows manufacturers to customize materials for different applications, ensuring optimal performance and functionality. See also Heat Treatment Annealing stage-Steps The heat treatment process is a vital technique in the manufacturing and engineering industries. By subjecting materials to controlled heating and cooling, heat treatment can significantly enhance their mechanical properties, durability, and performance. From improving hardness and strength to increasing wear resistance and machinability, heat treatment offers a wide range of benefits. Understanding the fundamentals of heat treatment empowers manufacturers to optimize material properties and create high-quality components for various applications. Heat treatment is a controlled process of heating and cooling metals to change their physical and mechanical properties without changing the shape of the metal. It is mainly done to make the metal stronger, softer, more durable, or to relieve internal stresses developed during manufacturing. Heat treatment is necessary to improve the metal's strength, hardness, ductility, and resistance to wear and tear. It is widely used in industries like automotive, aerospace, construction, and tool making to enhance the performance and life of metal components. Without heat treatment, many metal parts would fail early due to brittleness or weakness. Detailed Explanation: Heat treatment is a very important process in mechanical engineering and metalworking. It involves heating a metal to a specific temperature, holding it at that temperature for a certain period, and then cooling it in a specific way (like using air, water, or oil). This process changes the internal structure of the metal, known as its microstructure, which directly affects its properties such as hardness, strength, flexibility, and toughness. The purpose of heat treatment is not to melt or reshape the metal, but to improve how it behaves during use. When metals are cut, welded, forged, or cast, internal stresses may build up. These stresses can weaken the material over time. Heat treatment helps remove these stresses and prepares the metal for its intended use. There are many types of heat treatment methods, and each has its own purpose. Some methods make the metal harder for cutting tools, while others make it softer for shaping. Common heat treatment processes include annealing, hardening, tempering, normalizing, and case hardening. Why heat treatment is necessary Improves Mechanical Properties Heat treatment improves strength, toughness, and hardness. For example, cutting tools are hardened so they don't wear out quickly. Similarly, automotive and aerospace parts are heat treated to withstand heavy loads and harsh environments. Enhances Machinability and Formability Sometimes, metals are too hard to cut or shape. Heat treatment makes them softer and easier to work with. Annealing is a common process to soften metals and make them suitable for bending or machining. Relieves Internal Stresses During welding or machining, internal stresses develop in metal parts. These can cause cracks or deformation later. Heat treatment removes or reduces these stresses, increasing reliability and stability. Increases Wear and Corrosion Resistance Heat treatment can create a hard surface while keeping the inside soft and tough. This helps protect parts like gears, bearings, and engine components from wearing out too quickly. Some methods also improve resistance to rust and chemical damage. Improves Grain Structure and Homogeneity The grain structure of metals affects their strength and performance. Heat treatment refines and aligns the grain structure, making the metal more uniform and consistent throughout. Increases Service Life of Components Proper heat treatment makes metal components last longer and perform better. This is important in industries where safety and durability are important, such as railway, construction, and defense. Common Heat Treatment Processes Annealing Metal is heated and then cooled slowly. This softens the metal, improves ductility, and makes it easier to work with. Hardening Metal is heated to a high temperature and then cooled quickly (quenched). This increases hardness and strength but makes the metal brittle. Tempering After hardening, the metal is reheated to a lower temperature and then cooled. This reduces brittleness while keeping much of the hardness. Normalizing Metal is heated above its critical point and cooled in air. This improves toughness and grain structure. Case Hardening This method hardens only the outer layer of the part, keeping the inside soft and flexible. It is used for gears and tools that need a tough surface. Conclusion Heat treatment is a key process in mechanical engineering to make metals stronger, more flexible, or more durable based on their usage. It helps improve the performance and life of metal components by changing their internal structure. Whether it's softening metal for machining or hardening it for cutting tools, heat treatment is necessary to ensure metals perform well under stress and over time. It plays an important role in almost every industry that uses metals. Process of heating something to alter it Heat treating furnace at 1,800 °F (980 °C) Heat treating (or heat treatment) is a group of industrial, thermal and metalworking processes used to alter the physical, and sometimes chemical, properties of a material. The most common application is metallurgical. Heat treatments are also used in the manufacture of many other materials, such as glass. Heat treatment involves the use of heating or chilling, normally to extreme temperatures, to achieve the desired result such as hardening or softening of a material. Heat treatment techniques include annealing, case hardening, precipitation strengthening, tempering, carburizing, normalizing and quenching. Although the term heat treatment applies only to processes where the heating and cooling are done for the specific purpose of altering properties intentionally, heating and cooling often occur incidentally during other manufacturing processes such as hot forming or welding. Allotropes of iron, showing the differences in lattice structures between alpha iron (low temperature) and gamma iron (high temperature). The alpha iron has no spaces for carbon atoms to reside, while the gamma iron is open to the free movement of small carbon atoms. Photomicrographs of steel. Top: In annealed (slowly cooled) steel, the carbon precipitates forming layers of ferrite (iron) and cementite (carbide). Bottom: In quenched (quickly cooled) steel, the carbon remains trapped in the iron, creating great internal stresses in the needle or plate-like grains. Metallic materials consist of a microstructure of small crystals called "grains" or crystallites. The nature of the grains (i.e. grain size and composition) is one of the most effective factors that can determine the overall mechanical behavior of the metal. Heat treatment provides an efficient way to manipulate the properties of the metal by controlling the rate of diffusion and the rate of cooling within the microstructure. Heat treating is often used to alter the mechanical properties of a metallic alloy, manipulating properties such as the hardness, strength, toughness, ductility, and elasticity.[1] There are two mechanisms that may change an alloy's properties during heat treatment: the formation of martensite causes the crystals to deform intrinsically, and the diffusion mechanism causes changes in the homogeneity of the alloy.[2] The crystal structure consists of atoms that are grouped in a very specific arrangement, called a lattice. In most elements, this order will rearrange itself, depending on conditions like temperature and pressure. This rearrangement called allotropy or polymorphism, may occur several times, at many different temperatures for a particular metal. In alloys, this rearrangement may cause an element that will not normally dissolve into the base metal to suddenly become soluble, while a reversal of the allotropy will make the elements either partially or completely insoluble.[3] When in the soluble state, the process of diffusion causes the atoms of the dissolved element to spread out, attempting to form a homogenous distribution within the crystals of the base metal. If the alloy is cooled to an insoluble state, the atoms of the dissolved constituents (solutes) may migrate out of the solution. This type of diffusion, called precipitation, leads to nucleation, where the migrating atoms group together at the grain-boundaries. This forms a microstructure generally consisting of two or more distinct phases.[4] For instance, steel that has been heated above the austenizing temperature (red to orange-hot, or around 1,500 °F (820 °C) to 1,600 °F (870 °C) depending on carbon content), and then cooled slowly, forms a laminated structure composed of alternating layers of ferrite and cementite, becoming soft pearlite.[5] After heating the steel to the austenite phase and then quenching it in water, the microstructure will be in the martensitic phase. This is due to the fact that the steel will change from the austenite phase to the martensite phase after quenching. Some pearlite or ferrite may be present if the quench did not rapidly cool off all the steel.[4] Unlike iron-based alloys, most heat-treatable alloys do not experience a ferrite transformation. In these alloys, the nucleation at the grain-boundaries often reinforces the structure of the crystal matrix. These metals harden by precipitation. Typically a slow process, depending on temperature, this is often referred to as "age hardening".[6] Many metals and non-metals exhibit a martensite transformation when cooled quickly (with external media like oil, polymer, water, etc.). When a metal is cooled very quickly, the insoluble atoms may not be able to migrate out of the solution in time. This is called a "diffusionless transformation." When the crystal matrix changes to its low-temperature arrangement, the atoms of the solute become trapped within the lattice. The trapped atoms prevent the crystal matrix from completely changing into its low-temperature allotrope, creating shearing stresses within the lattice. When some alloys are cooled quickly, such as steel, the martensite transformation hardens the metal, while in others, like aluminum, the alloy becomes softer.[7][8] Phase diagram of an iron-carbon alloying system. Phase changes occur at different temperatures (vertical axis) for different compositions (horizontal axis). The dotted lines mark the eutectoid (A) and eutectic (B) compositions.The specific composition of an alloy system will usually have a great effect on the results of heat treating. If the percentage of each constituent is just right, the alloy will form a single, continuous microstructure upon cooling. Such a mixture is said to be eutectoid. However, If the percentage of the solutes varies from the eutectoid mixture, two or more different microstructures will usually form simultaneously. A hypo eutectoid solution contains less of the solute than the eutectoid mix, while a hypereutectoid solution contains more.[9] A eutectoid (eutectic-like) alloy is similar in behavior to a eutectic alloy. A eutectic alloy is characterized by having a single melting point. This melting point is lower than that of any of the constituents, and no change in the mixture will lower the melting point any further. When a molten eutectic alloy is cooled, all of the constituents will crystallize into their respective phases at the same temperature. A eutectoid alloy is similar, but the phase change occurs, not from a liquid, but from a solid solution. Upon cooling a eutectoid alloy from the solution temperature, the constituents will separate into different crystal phases, forming a single microstructure. A eutectoid steel, for example, contains 0.77% carbon. Upon cooling slowly, the solution of iron and carbon (a single phase called austenite) will separate into platelets of the phases ferrite and cementite. This forms a layered microstructure called pearlite. Since pearlite is harder than iron, the degree of softness achievable is typically limited to that produced by the pearlite. Similarly, the hardenability is limited by the continuous martensitic microstructure formed when cooled very fast.[10] A hypoeutectic alloy has two separate melting points. Both are above the eutectic melting point for the system but are below the melting points of any constituent forming the system. Between these two melting points, the alloy will exist as part solid and part liquid. The constituent with the higher melting point will solidify first. When completely solidified, a hypoeutectic alloy will often be in a solid solution. Similarly, a hypoeutectoid alloy has two critical temperatures, called "arrests". Between these two temperatures, the alloy will exist partly as the solution and partly as a separate crystallizing phase, called the "pro eutectoid phase". These two temperatures are called the upper (A3) and lower (A1) transformation temperatures. As the solution cools from the upper transformation temperature toward an insoluble state, the excess base metal will often be forced to "crystallize-out", becoming the pro eutectoid. This will occur until the remaining concentration of solutes reaches the eutectoid level, which will then crystallize as a separate microstructure. For example, a hypoeutectoid steel contains less than 0.77% carbon. Upon cooling a hypoeutectoid steel from the austenite transformation temperature, small islands of proeutectoid-ferrite will form. These will continue to grow and the carbon will recede until the eutectoid concentration in the rest of the steel is reached. This eutectoid mixture will then crystallize as a microstructure of pearlite. Since ferrite is softer than pearlite, the two microstructures combine to increase the ductility of the alloy. Consequently, the hardenability of the alloy is lowered.[11] Hypereutectoid steel A hypereutectic alloy also has different melting points. However, between these points, it is the constituent with the higher melting point that will be solid. Similarly, a hypereutectoid alloy has two critical temperatures. When cooling a hypereutectoid alloy from the upper transformation temperature, it will usually be the excess solutes that crystallize-out first, forming the pro-eutectoid. This continues until the concentration in the remaining alloy becomes eutectoid, which then crystallizes into a separate microstructure. A hypereutectoid steel contains more than 0.77% carbon. When slowly cooling hypereutectoid steel, the cementite will begin to crystallize first. When the remaining steel becomes eutectoid in composition, it will crystallize into pearlite. Since cementite is much harder than pearlite, the alloy has greater hardenability at a cost in ductility.[9][11] Time-temperature transformation (TTT) diagram for steel. The red curves represent different cooling rates (velocity) when cooled from the upper critical (A3) temperature. V1 (quenching) produces martensite. V2 (normalizing) produces both pearlite and martensite, V3 (annealing) produces bainite mixed with pearlite. Proper heat treating requires precise control over temperature, time held at a certain temperature and cooling rate.[12] With the exception of stress-relieving, tempering, and aging, most heat treatments begin by heating an alloy beyond a certain transformation, or arrest (A), temperature. This temperature is referred to as an "arrest" because at the A temperature the metal experiences a period of hysteresis. At this point, all of the heat energy is used to cause the crystal change, so the temperature stops rising for a short time (arrests) and then continues climbing once the change is complete.[13] Therefore, the alloy must be heated above the critical temperature for a transformation to occur. The alloy will usually be held at this temperature long enough for the heat to completely penetrate the alloy, thereby bringing it into a complete solid solution. Iron, for example, has four critical-temperatures, depending on carbon content. Pure iron in its alpha (room temperature) state changes to nonmagnetic gamma-iron at its A2 temperature, and weldable delta-iron at its A4 temperature. However, as carbon is added, becoming steel, the A2 temperature splits into the A3 temperature, also called the austenizing temperature (all phases become austenite, a solution of gamma iron and carbon) and its A1 temperature (austenite changes into pearlite upon cooling). Between these upper and lower temperatures the pro eutectoid phase forms upon cooling. Because a smaller grain size usually enhances mechanical properties, such as toughness, shear strength and tensile strength, these metals are often heated to a temperature that is just above the upper critical temperature, in order to prevent the grains of solution from growing too large. For instance, when steel is heated above the upper critical-temperature, small grains of austenite form. These grow larger as the temperature is increased. When cooled very quickly, during a martensite transformation, the austenite grain-size directly affects the martensitic grain-size. Larger grains have large grain-boundaries, which serve as weak spots in the structure. The grain size is usually controlled to reduce the probability of breakage.[14] The diffusion transformation is very time-dependent. Cooling a metal will usually suppress the precipitation to a much lower temperature. Austenite, for example, usually only exists above the upper critical temperature. However, if the austenite is cooled quickly enough, the transformation may be suppressed for hundreds of degrees below the lower critical temperature. Such austenite is highly unstable and, if given enough time, will precipitate into various microstructures of ferrite and cementite. The cooling rate can be used to control the rate of grain growth or can even be used to produce partially martensitic microstructures.[15] However, the martensite transformation is time-independent. If the alloy is cooled to the martensite transformation (Ms) temperature before other microstructures can fully form, the transformation will usually occur at just under the speed of sound.[16] When austenite is cooled but kept above the martensite start temperature Ms so that a martensite transformation does not occur, the austenite grain size will have an effect on the rate of nucleation, but it is generally temperature and the rate of cooling that controls the grain size and microstructure. When austenite is cooled extremely slowly, it will form large ferrite crystals filled with spherical inclusions of cementite. This microstructure is referred to as "sphereoidite". If cooled a little faster, then coarse pearlite will form. Even faster, and fine pearlite will form. If cooled even faster, bainite will form, with more complete bainite transformation occurring depending on the time held above martensite start Ms. Similarly, these microstructures will also form, if cooled to a specific temperature and then held there for a certain time.[17] Most non-ferrous alloys are also heated in order to form a solution. Most often, these are then cooled very quickly to produce a martensite transformation, putting the solution into a supersaturated state. The alloy, being in a much softer state, may then be cold worked. This causes work hardening that increases the strength and hardness of the alloy. Moreover, the defects caused by plastic deformation tend to speed up precipitation, increasing the hardness beyond what is normal for the alloy. Even if not cold worked, the solutes in these alloys will usually precipitate, although the process may take much longer. Sometimes these metals are then heated to a temperature that is below the lower critical (A1) temperature, preventing recrystallization, in order to speed-up the precipitation.[18][19][20] Steel castings after undergoing 12-hour 1,200 °C (2,190 °F) heat treatment. Complex heat treating schedules, or "cycles", are often devised by metallurgists to optimize an alloy's mechanical properties. In the aerospace industry, a superalloy may undergo five or more different heat treating operations to develop the desired properties. [citation needed] This can lead to quality problems depending on the accuracy of the furnace's temperature controls and timer. These operations can usually be divided into several basic techniques. Main article: Annealing (metallurgy) Annealing consists of heating a metal to a specific temperature and then cooling at a rate that will produce a refined microstructure, either fully or partially separating the constituents. The rate of cooling is generally slow. Annealing is most often used to soften a metal for cold working, to improve machinability, or to enhance properties like electrical conductivity. In ferrous alloys, annealing is usually accomplished by heating the metal beyond the upper critical temperature and then cooling very slowly, resulting in the formation of pearlite. In both pure metals and many alloys that cannot be heat treated, annealing is used to remove the hardness caused by cold working. The metal is heated to a temperature where recrystallization can occur, thereby repairing the defects caused by plastic deformation. In these metals, the rate of cooling will usually have little effect. Most non-ferrous alloys that are heat-treatable are also annealed to relieve the hardness of cold working. These may be slowly cooled to allow full precipitation of the constituents and produce a refined microstructure. Ferrous alloys are usually either "full annealed" or "process annealed". Full annealing requires very slow cooling rates, in order to form coarse pearlite. In process annealing, the cooling rate may be faster; up to, and including normalizing. The main goal of process annealing is to produce a uniform microstructure. Non-ferrous alloys are often subjected to a variety of annealing techniques, including "recrystallization annealing", "partial annealing", "full annealing", and "final annealing". Not all annealing techniques involve recrystallization, such as stress relieving.[21] Normalizing is a technique used to provide uniformity in grain size and composition (equiaxed crystals) throughout an alloy. The term is often used for ferrous alloys that have been austenitized and then cooled in the open air.[21] Normalizing not only produces pearlite but also martensite and sometimes bainite, which gives harder and stronger steel but with less ductility for the same composition than full annealing. In the normalizing process the steel is heated to about 40 degrees Celsius above its upper critical temperature limit, held at this temperature for some time, and then cooled in air. Stress-relieving is a technique to remove or reduce the internal stresses created in metal. These stresses may be caused in a number of ways, ranging from cold working to non-uniform cooling. Stress-relieving is usually accomplished by heating a metal below the lower critical temperature and then cooling uniformly.[21] Stress relieving is commonly used on items like air tanks, boilers and other pressure vessels, to remove a portion of the stresses created during the welding process.[22] Main article: Precipitation hardening Some metals are classified as precipitation hardening metals. When a precipitation hardening alloy is quenched, its alloying elements will be trapped in solution, resulting in a soft metal. Aging a "solutionized" metal will allow the alloying elements to diffuse through the microstructure and form intermetallic particles. These intermetallic particles will nucleate and fall out of the solution and act as a reinforcing phase, thereby increasing the strength of the alloy. Alloys may age " naturally" meaning that the precipitates form at room temperature, or they may age "artificially" when precipitates only form at elevated temperatures. In some applications, naturally aging alloys may be stored in a freezer to prevent hardening until after further operations - assembly of rivets, for example, maybe easier with a softer part. Examples of precipitation hardening alloys include 2000 series, 6000 series, and 7000 series aluminium alloy, as well as some superalloys and some stainless steels. Steels that harden by aging are typically referred to as maraging steels, from a combination of the term "martensite aging".[21] Main article: Quenching Quenching is a process of cooling a metal at a rapid rate. This is most often done to produce a martensite transformation. In ferrous alloys, this will often produce a harder metal, while non-ferrous alloys will usually become softer than normal. To harden by quenching, a metal (usually steel or cast iron) must be heated above the upper critical temperature (Steel: above 815~900 degrees Celsius[23]) and then quickly cooled. Depending on the alloy and other considerations (such as concern for maximum hardness vs. cracking and distortion), cooling may be done with forced air or other gases, (such as nitrogen). Liquids may be used, due to their better thermal conductivity, such as oil, water, a polymer dissolved in water, or a brine. Upon being rapidly cooled, a portion of austenite (dependent on alloy composition) will transform to martensite, a hard, brittle crystalline structure. The quenched hardness of a metal depends on its chemical composition and quenching method. Cooling speeds, from fastest to slowest, go from brine, polymer (i.e. mixtures of water + glycol polymers), freshwater, oil, and forced air. However, quenching certain steel too fast can result in cracking, which is why high-tensile steels such as AISI 4140 should be quenched in oil, tool steels such as ISO 1.2767 or H13 hot work tool steel should be quenched in forced air, and low alloy or medium-tensile steels such as XK1320 or AISI 1040 should be quenched in brine. Some Beta titanium based alloys have also shown similar trends of increased strength through rapid cooling.[24] However, most non-ferrous metals, like alloys of copper, aluminum, or nickel, and some high alloy steels such as austenitic stainless steel (304, 316), produce an opposite effect when these are quenched: they soften. Austenitic stainless steels must be quenched to become fully corrosion resistant, as they work-harden significantly.[21] Main article: Tempering (metallurgy) Untempered martensitic steel, while very hard, is too brittle to be useful for most applications. A method for alleviating this problem is called tempering. Most applications require that quenched parts be tempered. Tempering consists of heating steel below the lower critical temperature, (often from 400˚F to 1105˚F or 205˚C to 595˚C, depending on the desired results), to impart some toughness. Higher tempering temperatures (maybe up to 1,300˚F or 700˚C, depending on the alloy and application) are sometimes used to impart further ductility, although some yield strength is lost. Tempering may also be performed on normalized steels. Other methods of tempering consist of quenching to a specific temperature, which is above the martensite start temperature, and then holding it there until pure bainite can form or internal stresses can be relieved. These include austempering and martempering.[21] Tempering colors of steel Steel that has been freshly ground or polished will form oxide layers when heated. At a very specific temperature, the iron oxide will form a layer with a very specific thickness, causing thin-film interference. This causes colors to appear on the surface of the steel. As the temperature is increased, the iron oxide layer grows in thickness, changing the color.[25] These colors, called tempering colors, have been used for centuries to gauge the temperature of the metal. 350˚F (176˚C), light yellowish 400˚F (204˚C), light-straw 440˚F (226˚C), dark-straw 500˚F (260˚C), brown 540˚F (282˚C), purple 590˚F (310˚C), deep blue 640˚F (337˚C), light blue[26] The tempering colors can be used to judge the final properties of the tempered steel. Very hard tools are often tempered in the light to the dark straw range, whereas springs are often tempered to the blue. However, the final hardness of the tempered steel will vary, depending on the composition of the steel. Higher-carbon tool steel will remain much harder after tempering than spring steel (of slightly less carbon) when tempered at the same temperature. The oxide film will also increase in thickness over time. Therefore, steel that has been held at 400˚F for a very long time may turn brown or purple, even though the temperature never exceeded that needed to produce a light straw color. Other factors affecting the final outcome are oil films on the surface and the type of heat source used.[26] Main article: Differential heat treatment Many heat treating methods have been developed to alter the properties of only a portion of an object. These tend to consist of either cooling different areas of an alloy at different rates, by quickly heating in a localized area and then quenching, by thermochemical diffusion, or by tempering different areas of an object at different temperatures, such as in differential tempering. [citation needed] Main article: Differential hardening A differentially hardened katana. The bright, wavy line following the hamon, called the nioi, separates the martensitic edge from the pearlitic back. The inset shows a close-up of the nioi, which is made up of individual martensite grains (niye) surrounded by pearlite. The wood-grain appearance comes from layers of different compositions.Some techniques allow different areas of a single object to receive different heat treatments. This is called differential hardening. It is common in high quality knives and swords. The Chinese jian is one of the earliest known examples of this, and the Japanese katana may be the most widely known. The Nepalese Khukuri is another example. This technique uses an insulating layer, like layers of clay, to cover the areas that are to remain soft. The areas to be hardened are left exposed, allowing only certain parts of the steel to fully harden when quenched. [citation needed] Main article: Surface hardening Flame hardening is used to harden only a portion of the metal. Unlike differential hardening, where the entire piece is heated and then cooled at different rates, in flame hardening, only a portion of the metal is heated before quenching. This is usually easier than differential hardening, but often produces an extremely brittle zone between the heated metal and the unheated metal, as cooling at the edge of this heat-affected zone is extremely rapid. [citation needed] Main article: Induction hardening Induction hardening is a surface hardening technique in which the surface of the metal is heated very quickly, using a no-contact method of induction heating. The alloy is then quenched, producing a martensite transformation at the surface while leaving the underlying metal unchanged. This creates a very hard, wear-resistant surface while maintaining the proper toughness in the majority of the object. Crankshaft journals are a good example of an induction hardened surface.[27] Main article: Case hardening Case hardening is a thermochemical diffusion process in which an alloying element, most commonly carbon or nitrogen, diffuses into the surface of a monolithic metal. The resulting interstitial solid solution is harder than the base material, which improves wear resistance without sacrificing toughness.[21] Laser surface engineering is a surface treatment with high versatility, selectivity and novel properties. Since the cooling rate is very high in laser treatment, metastable even metallic glass can be obtained by this method. Main article: Cryogenic treatment Although quenching steel causes the austenite to transform into martensite, all of the austenite usually does not transform. Some austenite crystals will remain unchanged even after quenching below the martensite finish (Mf) temperature. Further transformation of the austenite into martensite can be induced by slowly cooling the metal to extremely low temperatures. Cold treating generally consists of cooling the steel to around -115˚F (-81˚C), but does not eliminate all of the austenite. Cryogenic treating usually consists of cooling to much lower temperatures, often in the range of -315˚F (-192˚C), to transform most of the austenite into martensite. Cold and cryogenic treatments are typically done immediately after quenching, before any tempering, and will increase the hardness, wear resistance, and reduce the internal stresses in the metal but, because it is really an extension of the quenching process, it may increase the chances of cracking during the procedure. The process is often used for tools, bearings, or other items that require good wear resistance. However, it is usually only effective in high-carbon or high-alloy steels in which more than 10% austenite is retained after quenching.[28][29] The heating of steel is sometimes used as a method to alter the carbon content. When steel is heated in an oxidizing environment, the oxygen combines with the iron to form an iron-oxide layer, which protects the steel from decarburization. When the steel turns to austenite, however, the oxygen combines with iron to form a slag, which provides no protection from decarburization. The formation of slag and scale actually increases decarburization, because the iron oxide keeps oxygen in contact with the decarburization zone even after the steel is moved into an oxygen-free environment, such as the coals of a forge. Thus, the carbon atoms begin combining with the surrounding scale and slag to form both carbon monoxide and carbon dioxide, which is released into the air. Steel contains a relatively small percentage of carbon, which can migrate freely within the gamma iron. When austenitized steel is exposed to air for long periods of time, the carbon content in the steel can be lowered. This is the opposite from what happens when steel is heated in a reducing environment, in which carbon slowly diffuses further into the metal. In an oxidizing environment, the carbon can readily diffuse outwardly, so austenitized steel is very susceptible to decarburization. This is often used for cast steel, where a high carbon-content is needed for casting, but a lower carbon-content is desired in the finished product. It is often used on cast-irons to produce malleable cast iron, in a process called "white tempering". This tendency to decarburize is often a problem in other operations, such as blacksmithing, where it becomes more desirable to austenize the steel for the shortest amount of time possible to prevent too much decarburization.[30] Usually the end condition is specified instead of the process used in heat treatment.[31] A modern, fully computerized case hardening furnace. Case hardening is specified by "hardness" and "case depth". The case depth can be specified in two ways: total case depth or effective case depth. The total case depth is the true depth of the case. For most alloys, the effective case depth is the depth of the case that has a hardness equivalent of HRC50; however, some alloys specify a different hardness (40-60 HRC) at effective case depth; this is checked on a Tukon microhardness tester. This value can be roughly approximated as 65% of the total case depth; however, the chemical composition and hardenability can affect this approximation. If neither type of case depth is specified the total case depth is assumed.[31] For case hardened parts the specification should have a tolerance of at least ±0.005 in (0.13 mm). If the part is to be ground after heat treatment, the case depth is assumed to be after grinding.[31] The Rockwell hardness scale used for the specification depends on the depth of the total case depth, as shown in the table below. Usually, hardness is measured on the Rockwell "C" scale, but the load used on the scale will penetrate through the case if the case is less than 0.030 in (0.76 mm). Using Rockwell "C" for a thinner case will result in a false reading.[31] Rockwell scale required for various case depths[31] Total case depth, min. [in] Rockwell scale 0.030 C 0.024 A 0.021 45 N 0.018 30 N 0.015 15 N Less than 0.015 "File hard" For cases that are less than 0.015 in (0.38 mm) thick a Rockwell scale cannot reliably be used, so file hard is specified instead.[31] File hard is approximately equivalent to 58 HRC.[32] When specifying the hardness either a range should be given or the minimum hardness specified. If a range is specified at least 5 points should be given.[31] Only hardness is listed for through hardening. It is usually in the form of HRC with at least a five-point range.[31] The hardness for an annealing process is usually listed on the HRB scale as a maximum value.[31] It is a process to refine grain size, improve strength, remove residual stress, and affect the electromagnetic properties... Furnaces used for heat treatment can be split into two broad categories: batch furnaces and continuous furnaces. Batch furnaces are usually manually loaded and unloaded, whereas continuous furnaces have an automatic conveying system to provide a constant load into the furnace chamber.[33] Batch systems usually consist of an insulated chamber with a steel shell, a heating system, and an access door to the chamber.[33] Many basic box-type furnaces have been upgraded to a semi-continuous batch furnace with the addition of integrated quench tanks and slow-cool chambers. These upgraded furnaces are a very commonly used piece of equipment for heat-treating.[33] Also known as a " bogie hearth", the car furnace is an extremely large batch furnace. The floor is constructed as an insulated movable car that is moved in and out of the furnace for loading and unloading. The car is usually sealed using sand seals or solid seals when in position. Due to the difficulty in getting a sufficient seal, car furnaces are usually used for non-atmosphere processes. [citation needed] Fluidised bed heat treatment line Similar in type to the car furnace, except that the car and hearth are rolled into position beneath the furnace and raised by means of a motor-driven mechanism, elevator furnaces can handle large heavy loads and often eliminate the need for any external cranes and transfer mechanisms.[33] Bell furnaces have removable covers called bells, which are lowered over the load and hearth by crane. An inner bell is placed over the hearth and sealed to supply a protective atmosphere. An outer bell is lowered to provide the heat supply.[33] Furnaces that are constructed in a pit and extend to floor level or slightly above are called pit furnaces. Workpieces can be suspended from fixtures, held in baskets, or placed on bases in the furnace. Pit furnaces are suited to heating long tubes, shafts, and rods by holding them in a vertical position. This manner of loading provides minimal distortion.[33] Salt baths are used in a wide variety of heat treatment processes including neutral hardening, liquid carburising, liquid nitriding, austempering, martempering and tempering. Parts are loaded into a pot of molten salt where they are heated by conduction, giving a very readily available source of heat. The core temperature of a part rises in temperature at approximately the same rate as its surface in a salt bath.[33] Salt baths utilize a variety of salts for heat treatment, with cyanide salts being the most extensively used. Concerns about associated occupation health and safety, and expensive waste management and disposal due to their environmental effects have made the use of salt baths less attractive in recent years. Consequently, many salt baths are being replaced by more environmentally friendly fluidized bed furnaces.[34] A fluidised bed consists of a cylindrical retort made from high-temperature alloy, filled with sand-like aluminum oxide particulate. Gas (air or nitrogen) is bubbled through the oxide and the sand moves in such a way that it exhibits fluid-like behavior, hence the term fluidized. The solid-solid contact of the oxide gives very high thermal conductivity and excellent temperature uniformity throughout the furnace, comparable to those seen in a salt bath.[33] Carbon steel Carburizing Diffusion hardening Induction hardening Retrogression heat treatment Nitriding

^ ZIA, Abdul Wasy; Zhou, Zhifeng; Po-wan, Shum.; Lawrence Li, Kwak Yan (24 January 2017). "The effect of two-step heat treatment on hardness, fracture toughness, and wear of different biased diamond-like carbon coatings". Surface and Coatings Technology. 320: 118–125. doi:10.1016/j.surfcoat.2017.01.089. ^ Shant P. Gupta (2002). Solid state phase transformations. Allied Publishers Private Limited. pp. 28–29. ^ Robert W. Cahn; Peter Haasen, eds. (1996). Physical Metallurgy. Vol. 2. Elsevier Science. pp. 10–11. ^ a b Alvarenga, H. D.; Van de Putte, T.; Van Steenberge, N.; Sietsma, J.; Terryn, H. (8 October 2014). "Influence of Carbide Morphology and Microstructure on the Kinetics of Superficial Decarburization of C-Mn Steels". Metallurgical and Materials Transactions A. 46: 123–133. doi:10.1007/s11661-014-2600-y. S2CID 136871961. ^ Physical Metallurgy 1996, pp. 136–198 ^ Gupta 2002, pp. 299–347 ^ Physical Metallurgy 1996, pp. 1508–1543 ^ Gupta 2002, pp. 501–518 ^ a b B.B. Patra; Biswajit Samantray (2011). Engineering Chemistry I. Dorling Kindersley. pp. 75–77. ^ Dossett, Jon L.; Boyer, Howard E. (2006). Practical heat treating. ASM International. pp. 17–22. ^ a b Dossett & Boyer 2006, pp. 17–22 ^ Rajan, T. V.; Sharma, C. P.; Sharma, Ashok (1992). Heat Treatment: Principles and Techniques. Prentence Hall. p. 1. ^ New Edge of the Anvil: A Resource Book for the Blacksmith by Jack Andrews --Shipjack Press 1994 Page 93--96 ^ Rajan & Sharma 1992, pp. 62–67 ^ Dossett & Boyer 2006, pp. 23–25 ^ The physics of phase transitions: concepts and applications By Pierre Papon, Jacques Leblond, Paul Herman Ernst Meijer - Springer-Verlag Berlin Heidelberg 2006 Page 66 ^ Rajan & Sharma 1992 ^ Dossett & Boyer 2006, p. 231 ^ Rajan & Sharma 1992, pp. 187–190, 321 ^ Manufacturing technology: foundry, forming and welding By Rao - Tata McGraw-Hill 1998 Page 55 ^ a b c d e f g Dossett & Boyer 2006, pp. 2–6 ^ "The National Board of Boiler and Pressure Vessel Inspectors". www.nationalboard.org. Archived from the original on 20 December 2010. Retrieved 29 April 2018. ^ Aviation Maintenance Technician Handbook (FAA-H-8983-30A ed.). Federal Aviation Administration. 2018. ^ Najdahmadi, A.; Zarei-Hanzaki, A.; Farghadani, E. (1 February 2014). "Mechanical properties enhancement in Ti–29Nb–13Ta–4.6Zr alloy via heat treatment with no detrimental effect on its biocompatibility". Materials & Design. 54: 786–791. doi:10.1016/j.matdes.2013.09.007. ISSN 0261-3069. ^ Light, its interaction with art and antiquities By Thomas B. Brill - Plenum Publishing 1980 Page 55 ^ a b c Andrews, Jack (1994). New Edge of the Anvil: a resource book for the blacksmith. pp. 98–99. ^ Surface hardening of steels: understanding the basics By Joseph R. Davis - ASM International 2002 ^ Heat treater's guide: practices and procedures for irons and steels By ASM International - ASM International 2007 Page 12-13 ^ Handbook of residual stress and deformation of steel by George E. Totten, Maurice A. H. Howes, Tatsuo Inoue - ASM International 2002 Page 331-337 ^ Steel Heat Treatment: Metallurgy and Technologies By George E. Totten -- CRC press 2007 Page 306--308 ^ a b c d e f g h i "PMPA's Designer's Guide: Heat treatment". Archived from the original on 2009-07-14. Retrieved 2009-06-19. ^ Phone interview with the quality control inspector for FPM, Elk Grove Village, IL. 06-21-2010 ^ a b c d e f g h ASM International Handbook Committee. (1991). ASM Handbook, Volume 04 - Heat Treating. ASM International. ^ "Made in the Midlands | Fluidised beds: A Green Alternative to Salt Baths". claytonholdings.madeinthemidlands.com. Archived from the original on 2016-02-07. Retrieved 2015-06-02. International Heat Treatment Magazine in English Reed-Hill, Robert (1994). Principles of Physical Metallurgy (3rd ed.). Boston: PWS Publishing. Wikimedia Commons has media related to Heat treatment. Retrieved from " Heat treatment is the process of heating and cooling metals, using specific predetermined methods to obtain desired properties. Both ferrous, as well as non-ferrous metals, undergo heat treatment before putting them to use. Over time, a lot of different methods have been developed. Even today, metallurgists are constantly working to improve the outcomes and cost-efficiency of these processes. For that, they develop new schedules or cycles to produce a variety of grades. Each schedule refers to a different rate of heating, holding, and cooling the metal. These methods, when followed meticulously, can produce metals of different standards with remarkably specific physical and chemical properties. There are various reasons for carrying out heat treatment. Some procedures make the metal soft, while others increase hardness. They may also affect the electrical and heat conductivity of these materials. Some heat treatment methods relieve stresses induced in earlier cold working processes. Others develop desirable chemical properties to metals. Choosing the perfect method really comes down to the type of metal and the required properties. In some cases, a metal part may go through several heat treatment procedures. For instance, some superalloys used in the aircraft manufacturing industry may undergo up to six different heat-treating steps to optimize them for the application. In simple terms, heat treatment is the process of heating the metal, holding it at that temperature, and then cooling it back. During the process, the metal part will undergo changes in its mechanical properties. This is because the high temperature alters the microstructure of the metal. And microstructure plays an important role in the mechanical properties of a material. The final outcome depends on many different factors. These include the time of heating, time of keeping the metal part at a certain temperature, rate of cooling, surrounding conditions, etc. The parameters depend on the heat treatment method, type of metal, and part size. Over the course of this process, the metal's properties will change. Among those properties are electrical resistance, magnetism, hardness, toughness, ductility, brittleness, and corrosion resistance. As we already discussed, the microstructure of alloys will change during heat treatment. Heating is carried out in line with a prescribed thermal profile. An alloy may exist in one of three different states when heated. It may either be a mechanical mixture, a solid solution, or a combination of both. A mechanical mixture is analogous to a concrete mixture where cement binds sand and gravel together. Sand and gravel are still visible as separate particles. With metal alloys, the mechanical mixture is held together by the base metal. On the other hand, in a solid solution, all the components are mixed homogenously. This means that they cannot be identified individually even under a microscope. Every state brings along different qualities. It is possible to change the state through heating according to the phase diagram. The cooling, though, determines the final outcome. It is possible for the alloy to end up in one of the three states, depending solely on the method. During the holding or soaking stage, the metal is kept at the achieved temperature. The duration of that depends on the requirements. For example, case hardening only requires structural changes to the surface of the metal in order to increase surface hardness. At the same time, other methods need uniform properties. In this case, the holding period is longer. The soaking time also depends on the material type and part size. Larger parts need more time when uniform properties are the objective. It just takes longer for the core of a large part to reach the required temperature. After the soaking stage is complete, the metal must be cooled in a prescribed manner. At this stage, too, structural changes occur. A solid solution on cooling may stay the same, become a mechanical mixture completely or partially, depending on various factors. Different media such as brine, water, oil or forced air control the rate of cooling. The sequence of cooling media named above is in decreasing order of effective rate of cooling. Brine absorbs heat fastest, while air is the slowest. It is also possible to use furnaces in the cooling process. The controlled environment allows for high precision when slow cooling is necessary. There are quite a few heat treatment techniques to choose from. Every one of them brings along certain qualities. The most common heat treatment methods include: Annealing Normalizing Hardening Ageing Stress relieving Tempering Carburization In annealing, the metal is heated beyond the upper critical temperature and then cooled at a slow rate. Annealing is carried out to soften the metal. It makes the metal more suitable for cold working and forming. It also enhances the metal's machinability, ductility, and toughness. Annealing is also useful in relieving stresses in the part caused due to prior cold working processes. The plastic deformations present are removed during recrystallization when the metal temperature crosses the upper critical temperature. Metals may undergo a plethora of annealing techniques such as recrystallization annealing, full annealing, partial annealing, and final annealing. 2. Normalizing Normalizing is a heat treatment process used for relieving internal stresses caused by processes such as welding, casting, or quenching. In this process, the metal is heated to a temperature that is 40° C above its upper critical temperature. This temperature is higher than the one used for hardening or annealing. After holding it at this temperature for a designated period of time, it is cooled in air. Normalizing creates a uniform grain size and composition throughout the part. Normalized steels are harder and stronger than annealed steel. In fact, in its normalized form, steel is tougher than in any other condition. This is why parts that require impact strength or need to support massive external loads will almost always be normalized. The most common heat treatment process of all, hardening is used to increase the hardness of a metal. In some cases, only the surface may be hardened. A workpiece is hardened by heating it to the specified temperature, then cooling it rapidly by submerging it into a cooling medium. Oil, brine, or water may be used. The resulting part will have increased hardness and strength, but the brittleness increases too simultaneously. Case hardening is a type of hardening process in which only the outer layer of the workpiece is hardened. The process used is the same but as a thin outer layer is subjected to the process, the resultant workpiece has a hard outer layer but a softer core. This is common for shafts. A hard outer layer protects it from material wear. When mounting a bearing to a shaft, it may otherwise damage the surface and dislocate some particles that then accelerate the wearing process. A hardened surface provides protection from that and the core still has the necessary properties to handle fatigue stresses. Ageing or precipitation hardening is a heat treatment method mostly used to increase the yield strength of malleable metals. The process produces uniformly dispersed particles within a metal's grain structure which bring about changes in properties. Precipitation hardening usually comes after another heat treatment process that reaches higher temperatures. Ageing, however, only elevates the temperature to medium levels and brings it down quickly again. Some materials may age naturally (at room temperature) while others only age artificially, i.e. at elevated temperatures. For naturally ageing materials, it may be convenient to store them at lower temperatures. Stress-relieving is especially common for boiler parts, air bottles, accumulators, etc. This method takes the metal to a temperature just below its lower critical border. The cooling process is slow and therefore uniform. This is done to relieve stresses that have built-in up in the parts due to earlier processes such as forming, machining, rolling, or straightening. Tempering is the process of reducing excess hardness, and therefore brittleness, induced during the hardening process. Internal stresses are also relieved. Undergoing this process can make a metal suitable for many applications that need such properties. The temperatures are usually much lower than hardening temperatures. The higher the temperature used, the softer the final workpiece becomes. The rate of cooling does not affect the metal structure during tempering and usually, the metal cools in still air. In this heat treatment process, the metal is heated in the presence of another material that releases carbon on decomposition. The released carbon is absorbed into the surface of the metal. The carbon content of the surface increases, making it harder than the inner core. Although ferrous metals account for the majority of heat-treated materials, alloys of copper, magnesium, aluminum, nickel, brass, and titanium may also be heat treated. About 80% of heat-treated metals are different grades of steel. Ferrous metals that can be heat treated include cast iron, stainless steel, and various grades of tool steel. Processes like hardening, annealing, normalizing, stress relieving, case hardening, nitriding, and tempering are generally done on ferrous metals. Copper and copper alloys are subjected to heat treatment methods such as annealing, ageing and quenching. Aluminum is suitable for heat treatment methods such as annealing, solution heat treating, natural and artificial ageing. Heat treatment for aluminum is a precision process. Process scope must be established and it should be controlled carefully at each stage for the desired characteristics. Evidently, not all materials are suitable for the forms of heat treatment. Similarly, a single material will not necessarily benefit from each method. Therefore, every material should be studied separately to achieve the desired result. Using the phase diagrams and available information about the effect the aforementioned methods have is the starting point. Although most people don't know what heat treatment is, it's actually an essential part of the manufacturing process. That's because heat treating allows a metal piece to be improved in order for the material to better withstand wear and tear. Heat treatment involves heating a metal or alloy to a specific temperature and then cooling it to harden the material. Heat treatment can be used at different stages in the manufacturing process to change certain properties of that metal or alloy. For example, you might use heat treatment to make it stronger, harder, more durable, or more ductile, depending on what the material needs in order to perform properly. Some notable industries in which heat treatment plays an important role include aircraft, automobiles, hardware–such as saws and axes, computers, spacecraft, military, and the oil and gas industry. How Does Heat Treatment Work? In order to achieve the desired effect, the metal or alloy is heated up to a specified temperature, sometimes as hot as 2400°F, held at that temperature for a certain amount of time, and then cooled. While it's hot, the metal's physical structure, also called the microstructure, changes, ultimately resulting in its physical properties being changed. The length of time the metal is heated for is called the 'soak time.' The length of soak time plays an important role in the characteristics of a metal, as metal soaked for a long amount of time will see different microstructure changes than metal soaked for a shorter period of time. The cooling process after the soak time also plays a part in the result of the metal. Metal may be cooled quickly, which is called quenching, or slowly in the furnace to make sure it achieves the desired result. The combination of the soak temperature, soak time, cooling temperature, and cooling duration all play a role in creating the desired properties in a metal or alloy. When the metal is heat-treated during the manufacturing process also determines what properties are changed, and some metals may even be treated multiple times. Knowing what temperatures to heat and cool metals at, as well as how long each step of the process should take for a specific metal or alloy is extremely complicated. Because of that, material scientists known as metallurgists, study the effects of heat on metal and alloys and provide precise information on how to perform these processes correctly. Manufacturers rely on this information to ensure their metal pieces will have the correct properties at the end of the process. Some common forms of heat treatments include: Hardening: When a metal is hardened, it's heated to a point where the elements in the material transform into a solution. Defects in the structure are then transformed by creating a reliable solution and strengthening the metal. This increases the hardness of the metal or alloy, making it less malleable.   Annealing: This process is used on metals like copper, aluminum, silver, steel, and brass. These materials are heated to a certain temperature, are held at that temperature until transformation occurs, and then are slowly air-dried. This process softens the metal, making it more workable and less likely to fracture or crack. Tempering: Some materials like iron-based alloys are very hard, making them brittle. Tempering can reduce brittleness and strengthen the metal. In the tempering process, the metal is heated to a temperature lower than the critical point to reduce brittleness and maintain hardness. Case Hardening: The outside of the material is hardened while the inside remains soft. Since hardening can cause materials to become brittle, case hardening is used for materials that require flexibility while maintaining a durable wear layer. Normalization: Similar to annealing, this process makes the steel more tough and ductile by heating the material to critical temperatures and keeping it at this temperature until transformation occurs. Why is Heat Treatment Important? Without heat treating metal, especially steel, metal parts for everything from airplanes to computers wouldn't function properly, or might not even exist in the first place. Non-ferrous metal parts in particular would be much weaker. Aluminum and titanium alloys, as well as bronze and brass, are all strengthened through heat treatment. Many of these metals are used in the production of cars, airplanes, and other products that rely on strong metals not only for performance but for safety as well. Because heat-treated metals are often stronger than non-heat treated metals, treating metal pieces upfront prevents corrosion, which won't result in the replacement of expensive metal parts later on or as frequently. This causes machines to run more cheaply and efficiently and prevents problems. Solutions from General Kinematics General Kinematics provides optimal equipment in order to improve and boost productivity in the heat treatment process and other manufacturing processes. There are various steps when dealing with heat treating metals, General Kinematics provides foundry equipment designed to aid in this process and to increase manufacturing productivity. Conveyors General Kinematics SPIRA-FLOW™ vibrating spiral elevator is ideal for heat-related treatments that require a long conveying path, but it condenses it into a spiral shape in order to take up less space. The Spiral-Flow is a great fit for manufacturing plants that are tight on space or want to optimize their use of space. General Kinematics offers a wide range of additional conveyors for a multitude of heat treatment needs. Whether you are looking to move your materials from point A to point B, heat, cool, or more GK has the equipment you need to improve your processing power. Feeders Feeding material into the desired heat treatment process is ideally performed by industrial material feeders. General Kinematics Two-Mass Vibratory Feeders are designed to withstand the harshest and most demanding applications. They are equipped to take on the most challenging material loads in order to keep your process moving smoothly. GK Feeders are engineered to order and are low maintenance, meaning less downtime and more productivity. General Kinematics offers a variety of high-performing industrial equipment designed for various industries. See what else General Kinematics has to offer and how our industry-leading equipment can help your organization.   Heat treatment is a controlled process of heating and cooling metals to change their physical and mechanical properties without changing the shape of the metal. It is mainly done to make the metal stronger, softer, more durable, or to relieve internal stresses developed during manufacturing. Heat treatment is necessary to improve the metal's strength, hardness, ductility, and resistance to wear and tear. It is widely used in industries like automotive, aerospace, construction, and tool making to enhance the performance and life of metal components. Without heat treatment, many metal parts would fail early due to brittleness or weakness. Detailed Explanation: Heat treatment is a very important process in mechanical engineering and metalworking. It involves heating a metal to a specific temperature, holding it at that temperature for a certain period, and then cooling it in a specific way (like using air, water, or oil). This process changes the internal structure of the metal, known as its microstructure, which directly affects its properties such as hardness, strength, flexibility, and toughness. The purpose of heat treatment is not to melt or reshape the metal, but to improve how it behaves during use. When metals are cut, welded, forged, or cast, internal stresses may build up. These stresses can weaken the material over time. Heat treatment helps remove these stresses and prepares the metal for its intended use. There are many types of heat treatment methods, and each has its own purpose. Some methods make the metal harder for cutting tools, while others make it softer for shaping. Common heat treatment processes include annealing, hardening, tempering, normalizing, and case hardening. Why heat treatment is necessary Improves Mechanical Properties Heat treatment improves strength, toughness, and hardness. For example, cutting tools are hardened so they don't wear out quickly. Similarly, automotive and aerospace parts are heat treated to withstand heavy loads and harsh environments. Enhances Machinability and Formability Sometimes, metals are too hard to cut or shape. Heat treatment makes them softer and easier to work with. Annealing is a common process to soften metals and make them suitable for bending or machining. Relieves Internal Stresses During welding or machining, internal stresses develop in metal parts. These can cause cracks or deformation later. Heat treatment removes or reduces these stresses, increasing reliability and stability. Increases Wear and Corrosion Resistance Heat treatment can create a hard surface while keeping the inside soft and tough. This helps protect parts like gears, bearings, and engine components from wearing out too quickly. Some methods also improve resistance to rust and chemical damage. Improves Grain Structure and Homogeneity The grain structure of metals affects their strength and performance. Heat treatment refines and aligns the grain structure, making the metal more uniform and consistent throughout. Increases Service Life of Components Proper heat treatment makes metal components last longer and perform better. This is important in industries where safety and durability are important, such as railway, construction, and defense. Common Heat Treatment Processes Annealing Metal is heated and then cooled slowly. This softens the metal, improves ductility, and makes it easier to work with. Hardening Metal is heated to a high temperature and then cooled quickly (quenched). This increases hardness and strength but makes the metal brittle. Tempering After hardening, the metal is reheated to a lower temperature and then cooled. This reduces brittleness while keeping much of the hardness. Normalizing Metal is heated above its critical point and cooled in air. This improves toughness and grain structure. Case Hardening This method hardens only the outer layer of the part, keeping the inside soft and flexible. It is used for gears and tools that need a tough surface. Conclusion Heat treatment is a key process in mechanical engineering to make metals stronger, more flexible, or more durable based on their usage. It helps improve the performance and life of metal components by changing their internal structure. Whether it's softening metal for machining or hardening it for cutting tools, heat treatment is necessary to ensure metals perform well under stress and over time. It plays an important role in almost every industry that uses metals. Heat treatment is the process of heating and cooling metals, using specific predetermined methods to obtain desired properties. Both ferrous, as well as non-ferrous metals, undergo heat treatment before putting them to use. Over time, a lot of different methods have been developed. Even today, metallurgists are constantly working to improve the outcomes and cost-efficiency of these processes. For that, they develop new schedules or cycles to produce a variety of grades. Each schedule refers to a different rate of heating, holding, and cooling the metal. These methods, when followed meticulously, can produce metals of different standards with remarkably specific physical and chemical properties. There are various reasons for carrying out heat treatment. Some procedures make the metal soft, while others increase hardness. They may also affect the electrical and heat conductivity of these materials. Some heat treatment methods relieve stresses induced in earlier cold working processes. Others develop desirable chemical properties to metals. Choosing the perfect method really comes down to the type of metal and the required properties. In some cases, a metal part may go through several heat treatment procedures. For instance, some superalloys used in the aircraft manufacturing industry may undergo up to six different heat-treating steps to optimize them for the application. In simple terms, heat treatment is the process of heating the metal, holding it at that temperature, and then cooling it back. During the process, the metal part will undergo changes in its mechanical properties. This is because the high temperature alters the microstructure of the metal. And microstructure plays an important role in the mechanical properties of a material. The final outcome depends on many different factors. 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In this process, the metal is heated to a temperature that is 40° C above its upper critical temperature. This temperature is higher than the one used for hardening or annealing. After holding it at this temperature for a designated period of time, it is cooled in air. Normalizing creates a uniform grain size and composition throughout the part. Normalized steels are harder and stronger than annealed steel. In fact, in its normalized form, steel is tougher than in any other condition. This is why parts that require impact strength or need to support massive external loads will almost always be normalized. The most common heat treatment process of all, hardening is used to increase the hardness of a metal. In some cases, only the surface may be hardened. A workpiece is hardened by heating it to the specified temperature, then cooling it rapidly by submerging it into a cooling medium. Oil, brine, or water may be used. The resulting part will have increased hardness and strength, but the brittleness increases too simultaneously. Case hardening is a type of hardening process in which only the outer layer of the workpiece is hardened. The process used is the same but as a thin outer layer is subjected to the process, the resultant workpiece has a hard outer layer but a softer core. This is common for shafts. A hard outer layer protects it from material wear. When mounting a bearing to a shaft, it may otherwise damage the surface and dislocate some particles that then accelerate the wearing process. A hardened surface provides protection from that and the core still has the necessary properties to handle fatigue stresses. Ageing or precipitation hardening is a heat treatment method mostly used to increase the yield strength of malleable metals. The process produces uniformly dispersed particles within a metal's grain structure which bring about changes in properties. Precipitation hardening usually comes after another heat treatment process that reaches higher temperatures. Ageing, however, only elevates the temperature to medium levels and brings it down quickly again. Some metals may age naturally (at room temperature) while others only age artificially, i.e. at elevated temperatures. For naturally ageing materials, it may be convenient to store them at lower temperatures. Stress-relieving is especially common for boiler parts, air bottles, accumulators, etc. This method takes the metal to a temperature just below its lower critical border. The cooling process is slow and therefore uniform. This is done to relieve stresses that have built-up in the parts due to earlier processes such as forming, machining, rolling, or straightening. Tempering is the process of reducing excess hardness, and therefore brittleness, induced during the hardening process. Internal stresses are also relieved. Undergoing this process can make a metal suitable for many applications that need such properties. The temperatures are usually much lower than hardening temperatures. The higher the temperature used, the softer the final workpiece becomes. The rate of cooling does not affect the metal structure during tempering and usually, the metal cools in still air. In this heat treatment process, the metal is heated in the presence of another material that releases carbon on decomposition. The released carbon is absorbed into the surface of the metal. The carbon content of the surface increases, making it harder than the inner core. Although ferrous metals account for the majority of heat-treated materials, alloys of copper, magnesium, aluminum, nickel, brass, and titanium may also be heat treated. About 80% of heat-treated metals are different grades of steel. Ferrous metals that can be heat treated include cast iron, stainless steel, and various grades of tool steel. Processes like hardening, annealing, normalizing, stress relieving, case hardening, nitriding, and tempering are generally done on ferrous metals. Copper and copper alloys are subjected to heat treatment methods such as annealing, ageing and quenching. Aluminum is suitable for heat treatment methods such as annealing, solution heat treatment, natural and artificial ageing. Heat treatment for aluminum is a precision process. Process scope must be established and it should be controlled carefully at each stage for the desired characteristics. Evidently, not all materials are suitable for the forms of heat treatment. Similarly, a single material will not necessarily benefit from each method. Therefore, every material should be studied separately to achieve the desired result. Using the phase diagrams and available information about the effect the aforementioned methods have is the starting point. Heat treatment is a critical and complex element in the manufacturing of gears that greatly impacts how each will perform in transmitting power or carrying motion to other components in an assembly. Heat treatments optimize the performance and extend the life of gears in service by altering their chemical, metallurgical, and physical properties. These properties are determined by considering the gear's geometry, power transmission requirements, stresses at different points within a gear under load, load cycling rates, material type, mating part designs, and other operating conditions. Heat treatments improve physical properties such as surface hardness, which imparts wear resistance to prevent tooth and bearing surfaces from simply wearing out. Heat treatments also improve a gear's fatigue life by generating subsurface compressive stresses to prevent pitting and deformation from high contact stresses on gear teeth. These same compressive stresses prevent fatigue failures in gear roots from cyclic tooth bending. Physical properties such as surface hardness, core hardness, case depth, ductility, strength, wear resistance and compressive stress profiles can vary greatly depending on the type of heat treatment applied. For any given type of heat treatment the results can be tailored by modifying process parameters such as heating source, temperatures, cycle times, atmospheres, quench media, and tempering cycles to meet specific application requirements. Figure 1: Typical press quench equipment and tooling design (Source: The Heat Treat Doctor: Fundamentals of Press Quenching by Dan Herring, Industrial Heating April, 1995). Besides selecting heat treatments that will produce a set of desired physical properties, manufacturing engineers want to minimize distortion of dimensions from heat treatment such that final proper fit into a gearbox can be achieved. Many gears are machined into an oversized condition prior to heat treatment so that a planned amount of grind stock may be removed after the process in order to meet dimensional requirements. By selecting heat treatment processes where distortion is reduced, the amount of grind stock needed may be reduced to minimize machining on hardened surfaces after heat treatment and thereby reduce the overall costs of manufacturing. Removing too much of the outermost portion of a case hardened gear that distorted excessively will also negatively impact the fatigue properties and wear life performance. Some heat treatment processes are designed to treat the entire surface of a gear, while others are selective in nature. Induction hardening or selective heating may be employed to harden just the gear teeth only, which can be an effective method of reducing the distortion in a gear. Masking of journals and keyways may be employed in case hardening processes to keep them soft and allow for easier grind stock removal after heat treatment. Reduction of distortion by intelligent heat treatment process design allows manufacturing engineers to improve the performance and/or reduce the overall costs of manufacturing a gear. Fig. 2: Two fully automated low pressure carburizing furnace lines (Bodycote-Livonia, Michigan). In all cases, gear design engineers understand that heat treatments play a complex and vital role in both the ease of manufacturing and the performance of the gears they make. Today, many options exist for the heat treatment of gears. Proper selection and design of the heat treatment process can greatly affect performance, ease of manufacture, and economics of a component. This paper will focus on a variety of different processes and highlight some benefits and disadvantages of each. Heat Treating Basics To understand heat treating, a basic knowledge of metallurgy is needed. Iron, when combined with small percentages of carbon, forms steel. Plain carbon steels typically contain 1 percent or less carbon in combination with iron. The maximum hardness that any plain carbon steel can achieve during heat treatment is primarily a function of its carbon content. Higher carbon content steels are capable of being hardened to higher hardness values than lower carbon content steels. To make alloy steels, small percentages of other elements such as Cr, Ni, Mo, Si, B, V, Ti, Al, N, Nb, W, and Cu (to name the most common) are added to steel. These alloying elements are added in order to increase hardenability or enhance specific properties such as toughness or resistance to softening from heat build-up. For heat treaters the higher hardenability allows for slower quenching, which means distortion can be kept to lower levels in more highly alloyed steels. Steels can be annealed by thermally processing at a high temperature and slow cooling to soften it. In this soft and malleable state it can be machined, formed, hobbed, and ground easily into a desired shape. What makes steel industrially important is that it can be hardened after the material has been formed or shaped in the soft state to a desired geometry. By use of a thermal processing cycle where steel is heated to austenitizing temperatures and rapidly quenched, the near-finished components can be hardened to improve wear resistance, strength, and hardness. After quenching to the maximum hardness achievable, which is determined by the steel's carbon content, the steel may then be tempered down to a lower hardness to improve ductility and toughness at the expense of slightly reducing the strength, hardness, and wear characteristics of the material. Figure 3: Hardness and compressive stress profiles generated by LPC (compare to Fig. 4). What actually occurs in steel during heat treating are phase transformations as atoms rearrange themselves into different crystal structures. The starting point of most heat treated parts is an annealed material. In fact, when purchasing steel it is generally in the annealed condition. An annealed structure is a combination of primarily ferrite (Fe, pure iron) and iron carbide (Fe3C, cementite). These will be in the form of alternating layers of ferrite and Fe3C (pearlitic structure), or ferrite with dispersed Fe3C spheres or spheroids (spherodized structure). When steel is heated above its austenitizing temperature, it transforms into the austenite structure. An approximate austenitizing temperature for most plain carbon steels is around 1330ºF and varies by exact grade of steel. Once full transformation of the steel to an austenite structure has occurred the austenite may be quenched (cooled rapidly), and that austenite structure will transform to a martensite structure. This transformation of austenite to martensite is the hardening process. The martensite structure yields the highest hardness and tensile strength properties of any structure for that steel. Producing a martensitic structure from austenite is the goal in hardening heat treatment of steels. One critical aspect of this hardening process is the cooling rate employed during quenching. Each grade of steel requires that a certain minimum cooling rate be achieved during quenching or the transformation from austenite to martensite will not occur. Austenitized steels held at high temperature and quenched too slowly down to ambient temperature will not transform from austenite to a martensitic structure. They will instead revert back a softer mix of ferrite and cementite again. Table 1 summarizes the methods in common use today for heat treatment of gears. Each method has its place; some are perfect for high volumes, while others are practical only on a piece-by-piece basis. Some improve all metallurgical properties, while others improve only one or two. Table 1: Common heat-treating methods for gears. Neutral Hardening There are two general classifications of heat treatments used for hardening steels: neutral hardening, and case hardening. Neutral hardening refers to maintaining the carbon potential of the atmosphere at the same percentage as the carbon in the steel during the hardening cycle. This means that carbon is entering and leaving the surface of the steel at the same rate, and no net gain or net loss of carbon atoms inside the surface of the steel occurs. Many gears are neutral hardened, but for the most demanding applications case hardening processes, such as carburizing and nitriding, are the preferred methods due to their improved wear characteristics and mechanical properties. Fig. 4: Hardness and compressive stress profiles generated by atmosphere carburizing (compare to Fig. 3). Atmosphere Carburizing Carburizing, the most widely used form of surface hardening, is the process of diffusing carbon into the surface of low carbon steel at elevated temperatures. This results in a high carbon case forming just inside the surface of a low carbon component. During quenching from austenitizing temperatures the austenite will transform to martensite, and the higher carbon case will have a high hardness while the lower carbon core material will have a lower hardness. The goal of this process is to produce a hard, strong, wear resistant outer surface while retaining a softer, ductile tough core. When austenite transforms to martensite during quenching, a volume expansion occurs in the material and it grows. The volumetric expansion in the case is greater than the volume expansion in the lower carbon, lower hardness core structure. This difference in size changes puts the carburized surface of the part into a state of compression, which makes it stronger. For example, when a force is applied to a gear tooth, it first has to overcome these compressive forces before beginning to put the surface of the tooth in tension. In order to deform this material, it requires a force that exceeds the combination of overcoming the compressive stresses present in addition to the normal yield strength of the material. These compressive stresses caused by differences in volume expansion rates between the case and core improves the overall tensile and yield strength of the carburized case inside a gear tooth. It is these compressive stresses that resist deformation from high contact stresses present as gear teeth press and roll against each other. These compressive stresses also increase fatigue life by helping to prevent cracking in tooth roots as the teeth are cyclically loaded and unloaded with bending stresses. The high carbon, high hardness surface of the carburized case also resists wear and scoring caused by friction as gear teeth rub and wear against each other. One can't discuss heat treating gears without discussing distortion, which occurs for a variety of reasons. One source is pre-existing residual stresses present in the material caused by prior operations such as steelmaking, rolling, forming, forging, casting, machining, and grinding. As the material begins to heat up during carburizing, these residual stresses present in the material relieve and cause the gears to distort if these stresses were large or non-uniform. A second source of distortion is high temperature creep during processing. Gravity is the enemy of many gear designs during thermal processing, especially in carburising, where high temperatures and long processing times are the norm. At high temperatures, steel has little strength and can sag and bend under gravity's force if sections of a part are not properly supported or components not stood up or hung perfectly straight. Spending the extra time to fixture parts correctly and designing customized fixtures to properly support a gear during exposure to high temperatures can save many hours of straightening and machining afterwards. Some part shapes such as long shafts are best racked in vertical orientations to maintain straightness while other shapes such as rings are better if laid flat horizontally to maintain roundness. Selection and experience in designing heat treatment fixtures can dramatically affect the results. A third source of distortion is quenching, which is typically the main offender in distorting parts during heat treatment. The ideal quench is the slowest quench that will uniformly pull heat out of the part, while still fully transforming the surface to martensite and achieving the desired case and core properties. This sounds easy enough, but in practice it can be quite difficult given the design and complex shape of many gears. Due to variations in customers' part geometries, limitations in fixture designs, non-uniform quench tank agitation, and part-to-part or part-to-fixture interactions, it is the most difficult distortion mechanism to resolve and predict. Even within a single part it's possible to have some thinner sections of a component cool faster than thicker sections causing one area to transform earlier than another and warp dimensions as the transformations with their associated volume expansions occur at different times during a quench. When distortion occurs to an unacceptable degree, solutions need to be found. After exhausting all the variations of processing parameters, fixturing methods, quench modifications, and ensuring parts are free from stress prior to heat treatment, other options need to be considered. This can be as simple as a straightening step, or as difficult as re-engineering the part. Some other methods of heat treating may provide more effective solutions to reducing distortion as well. Processes such as press quenching, tooth to tooth induction hardening, vacuum carburizing with gas quenching, and nitriding are employed when excessive distortion results during conventional carburizing of specific gear geometries. Figure 5: LPC process: carburized case in gear root (left), carburized case in gear tooth (right). Press Quenching of Gears The art of press quenching while being around for decades remains somewhat of a mystery to the engineering world, and even our own heat treating industry. In basic form, gears are carburized in large batches, slow cooled, reheated individually, and then quenched rapidly under some form of restraint to minimize distortion. The main dimensions that are restrained during press quenching are the flatness of the gear and the roundness of the bore in relation to the hub. The quenching equipment utilized is referred to as a press. They are either pneumatic or hydraulic in design, depending on the individual piece of equipment. The press has a lower die assembly that floats in nature and becomes stationary during the quench process. The upper die uses a primary and secondary upper pressure system that has two levels of controls through an outer and inner cylinder assembly. Depending on the press being used the maximum die pressure is different. When the gear is transferred to the press and placed on the die for quenching, it is restrained through the use of tooling designed specially for the gear being quenched. Oil flow becomes critical to the success of the pressing operation to minimize any distortion. The oil flow comes up from the oil reservoir through the chambers or holes within the lower die assembly, then circulating up and around the table to the oil flow rings based on the lower die table. The oil flow can be controlled through the manipulation of oil flow rings, which are located underneath the support rings. The oil flow can be restricted or wide open depending on the gear being quenched. This flow is regulated through timer controlled valves. The inner cylinder force is exerted against the rim of the gear to address flatness while the outer cylinder can be used to apply pressure to the face of the hub or to apply pressure to expand out an expander mandrel in the attempt to control the spline or bore sizing. Whether a plug or an expander is used in a bore depends upon what is trying to be accomplished. An expander is employed when the heat treater is trying to expand the tooling out to meet an intended bore diameter prior to the actually quenching the part. The intent is to minimize any "out of round" conditions that may occur. Larger bore diameter gears with thin wall thicknesses are prime candidates for the use of an expander to prevent any out of round conditions. A plug is used for holding a bore dimension. The plug is ground to a size close to the intended bore diameter. The heat treater is trying to have the bore cool or shrink uniformly to a certain dimension. A finish grinding operation of the bore is usually performed after plug quenching. Figure 6: No presence of intergranular oxidation after LPC process. The focus on gear press quenching should not be on the use of tooling. It has been taught that the best gear starts with the gear blank. Addressing the forging operation for the gear blank is important. In the forging operation, the direction of the grain pattern is critical such that the part will not have non-uniform residual stresses present. It is important that the blank also be normalized or annealed at temperatures that exceed the planned carburizing temperature by 50ºF. It is also important to ensure that the cycle time at temperature is held for a proper length of time. Insufficient time or temperature during normalizing or annealing will result in greater distortion being present during subsequent heat treatment steps. It is often recommended to perform a subcritical stress relieving operation after the rough machining of the gear blank to help minimize distortion in the final heat treating operation. While not considered absolutely necessary, it does help reduce distortion and improve the final quality of the part. Another concern that comes up in gear hardening is the tapering of the bore diameter through the length of the bore. This arises due the sectional changes present in some gears along their axis. The use of an expander and using various pressures on the inner cylinder will result in minimizing tapering. Tapering cannot be eliminated in some gear designs, but it can be minimized. When designing gears where press quenching is planned, it is recommended to have the heat treater involved from the design stage to understand how it will affect the final product. Press quenching is not the lowest-cost hardening process available, but it is a competitive process among today's gear hardening processes. In many cases press quenching is the only option, as distortion from conventional carburizing and quenching processes can be too excessive on some sensitive gear geometries. LCP/High Pressure Gas Quench Low Pressure Carburizing (LPC) with high pressure gas quench is a relatively new carburizing technology that has become more widely used during the last decade. It has become the popular choice of carburizing treatment for automotive transmission gears over the last 10 years with General Motors, Ford, Chrysler, and many foreign automakers now adopting this process. Many fuel injectors are currently carburized using this technology. Some aerospace components are also being low pressure carburized, with rotorcraft transmission gearing being another early adopter of LPC. Figure 7 Figure 7: Dual frequency induction patter (left), single frequency induction patter (right). Figure 8: Single-tooth hardening. LPC equipment comes in a variety of forms from different furnace manufacturers that all have different concepts and designs. In general, the equipment consists of vacuum chambers capable of heating parts to carburizing temperatures and capable of injecting small amounts of hydrocarbon gases at low pressure that act as a carbon source. In addition to the carburizing cells there are quenching cells where carburized hot loads may be cooled using high pressures of inert gases to rapidly cool the parts allowing hardening to occur by transforming austenite to martensite in the case and core structure. The gas quench cells are equipped with powerful fans and are capable of injecting gases typically up to 20 bar positive pressure in conjunction with heat-exchangers using chilled water to quickly remove heat from the quenching gases. The most common quenching media is high pressure nitrogen gas, and the more common carburizing gases are propane and acetylene. Many furnace manufacturers are using different gases, however, and blends of gases as carbon sources and quench gases. High hardenability alloys are required for LPC and high pressure gas quench. Typical grades of materials used are 8620, 5120, 4118, 17CrNiMo6, 9310, 3310, 8822H, 4822, and 8630. Lower hardenability plain carbon steels that can be carburized and oil quenched simply cannot be hardened using a gas quench because they will not properly transform as cooling rates are too slow. Even with high hardenability grades some consideration must be given to core hardness, as the gas quench will produce lower core hardness compared to oil quenched parts. A major advantage of LPC is that these same slow cooling rates during gas quenching translate into low distortion from quenching. Many parts that cannot be successfully oil quenched and maintain required dimensional tolerances are able to be LPC processed with a gas quench and yield acceptable dimensions. By eliminating the non-uniform cooling of parts associated with liquid quenches that have vapor, boiling, and convective cooling all taking place simultaneously and replacing it with gas quenches that have slower cooling rates and are more uniform and purely convective, distortion can be greatly reduced as gear surfaces are more uniformly cooled at slower rates. LPC with gas quenching can sometimes eliminate post-heat treatment straightening or clamp tempering operations, reduce grind stock allowances and hard machining, or replace more costly processes such as press quenching of individual gears. A second advantage of LPC is cleanliness of the parts after processing. The finished parts emerge from the furnace very clean. At times it is almost difficult to identify the heat-treated and non heat-treated parts. For this reason the heat-treated parts are slightly discolored, using the discoloration process to identify the heat-treated parts. In comparison, conventional carburizing uses oil quenching where the oil will burn onto the surfaces and finished parts are often dark, sooty, and have oil residue left on the surfaces. Another advantage of the LPC process is that it has the capability to utilize a higher carbon potential atmosphere during the boost thus obtaining higher hardness values deeper into the case in comparison to the conventional carburizing. This higher hardness deeper into the surface before transitioning to the core imparts greater compressive stresses to the surface case material and improves the fatigue properties and resistance to deformation by high single point rolling contact stresses on gear teeth. Another advantage of LPC processing over conventional carburizing is the depth of case attainable in gear tooth roots. The pitch to root ratio of the effective case depth after LPC is remarkably uniform. Oftentimes in conventional carburizing of gears, the case depth in the roots of teeth may only amount to half the case depth present at the mid-pitch tooth location. With LPC processing, the effective case depth present in the gear roots is nearly equivalent to the case depth present at the gear tooth midpitch location. This deeper case depth present in the gear tooth roots enhances fatigue life under tooth bending conditions and will outperform conventional carburized parts in this aspect. Another advantage of LPC is the absence of any inter-granular oxidation (IGO) on the surface of the part. This saves the gear manufacturer from grinding off the case to remove the IGO and saves valuable time and manufacturing costs. Typically .0003" to .0007" deep IGO will be present on any gears carburized in conventional endothermic atmosphere furnaces. The LPC process produces excellent metallurgical and dimensional results which are required for high performance transmission gears. There are many types of gears and products well-suited for the LPC process and the advantages of this process have been outlined above. The main disadvantages of this process are that LPC equipment is capital intensive and the consumables are expensive. Process engineering, operation, and maintenance require higher skill levels than traditional carburizing. There is also a limitation of load sizes that can be processed as the gas quenching requires that lighter loads be processed in order to cool them rapidly enough. Gas Nitriding The gas nitriding process for case hardening of alloy steels allows complex configurations to be treated with minimal distortion. This process is performed at low subcritical temperatures and completely avoids the problems of structural transformations associated with high temperature austenitizing and quenching of steel during carburizing. Earlier in this article we detailed the three causes for distortion in carburizing which included stress relieving of pre-existing residual stresses, high temperature creep distortion, and phase transformations upon quenching. Since there are no phase transformations at low nitriding temperatures, there is no distortion from phase changes. There is little concern for distortion due to high temperature creep at the low subcritical nitriding temperatures. That leaves only stress relief of residual stresses as a possible cause of distortion during nitriding. In order to eliminate this source of distortion a typical manufacturing sequence for nitrided gears would be to rough machine, stress relieve at 50 ºF above the nitriding temperature, final machine putting as little stress into the parts as possible, and then nitride. Nitriding is often performed on finish-machined components with little distortion and usually requires no post-heat treatment machining to clean up the tolerances. The nitriding process basically consists of placing steel surfaces at nitriding temperatures in contact with ammonia gas (NH_3). The ammonia dissociates at the steel surface providing atomic nitrogen which can then diffuse into the gear, react with specific alloying elements in the steel, and form alloy nitrides which creates a hardened wear resistant case below the gear's surface. There are many benefits of the gas nitriding process. Its purpose is to produce a very hard, wear resistant, load bearing case in relatively inexpensive alloy steels. The low treatment temperatures keep distortion and growth to a minimum and it is typically performed on finish-machined parts. This process is very simple to run and has fewer variables to control than the other case hardening processes discussed earlier. The lack of quenching which is a major source of variation in carburizing results is not present in nitriding and allows for better control and greater repeatability. The nitrided case also is not softened or tempered like carburized gears, which start to lose hardness at temperatures as low as 300ºF. Nitrided cases will not soften until exposed to temperatures above 1000ºF and can withstand high service temperatures. Isolated surfaces can be masked from nitriding and left soft for ease of machining, welding, or other purposes. The corrosion resistance of some low alloy steels is also slightly improved by nitriding. Some limitations of gas nitriding include only being able to achieve shallow case depths (0.030" max for some materials) due to the low diffusion temperatures. The nitriding alloy selections are limited to materials that contain Cr, Mo, V, Ti, W, and Al alone or in combination. There are occasional problems with spalling of the case if nitriding networks form, but this can be minimized with proper controls. Nitrided stainless steels lose much of their corrosion resistance by nitriding as chromium becomes bonded to nitrogen, which breaks down the protective chromium oxide layer normally present on stainless surfaces. The gas nitriding process is a readily available heat treatment process that creates an extremely hard, load bearing wear resistant surface with depths ranging from .005" to .025" depth. It can be performed on many commonly available alloy steels with minimal size change and high retention of core mechanical properties. Induction Hardening Gear Teeth Induction heat treating is localized heat treatment used to increase the fatigue life, strength, and wear resistance of a component. Induction hardening is accomplished by placing the part inside an alternating magnetic field causing an electrical current to form at the surface. Heat is generated as a result of the I2R losses in the material and allows heat treaters to selectively austenitize only the surface material of a component while leaving the core material untransformed. Not only is the surface only selectively heated, but induction allows only those desired surfaces to be heated while other surfaces may be left cold. In the case of gears it is possible to only austenitize the near surface of a single tooth leaving the balance of the part cold during processing. The heated gear surface is subsequently quenched in either water, oil, or a polymer based quench to transform the austenite into martensite thereby increasing hardness in the required area while leaving the remainder of the component virtually undisturbed. Gear Hardening: There are numerous factors that determine the appropriate induction hardening process to choose. Items such as geometry, permeability of the material, and desired mechanical properties will dictate processing variables such as frequency, power density, and heat time. There are many frequency selections to choose from when hardening gears. The relationship between frequency and current penetration depth are inversely proportional. Such that lower frequencies cause the current to form at deeper depths while higher frequencies generate heat immediately adjacent to the surface. Tooth form is a significant factor when selecting the correct frequency, as high frequencies will heat the tooth tips first and low frequencies will heat the roots first. Power density and heat time are crucial to achieving the desired mechanical properties with the least amount of dimensional movement and associated risk of cracking. When calculating power densities a target value of 12 KW/in2 should be used to minimize total heat penetration into the component core. Heat time should always be optimized to achieve full transformation to austenite at the desired hardening depth. Profile Induction Hardening: Profile induction hardening produces a tough core with associated tensile stresses and a hardened surface layer that exhibits compressive stress in the tips, flanks, and roots. Extensive product validation testing has determined that this combination of stresses best extend the component's fatigue life and wear resistance over other types of induction hardening while also producing the least amount of dimensional movement. The most common method of obtaining a profile hardening pattern is to use a "blend" of frequencies to actually heat the tips, flanks, and roots concurrently. This is accomplished by simultaneously generating high and low frequencies and passing them through the inductor at the same time. This type of power supply is relatively new to the market and is referred to as a "simultaneous dual frequency" generator. Most of these units allow the technician to individually adjust the intensity of the various frequencies seen by the part. This provides them the flexibility to customize or sculpt the shape of the pattern to the specific geometry of the tooth. Single Tooth Hardening: Single tooth hardening is primarily used to induction heat treat gear teeth to improve strength and wear characteristics. The process is accomplished by hardening one tooth root at a time. After each root has been hardened the system indexes the part to the next position and the process begins again. This process is time consuming as a 55 tooth gear will take 55 hardening cycles to complete. However, it is primarily used to harden very large, low volume parts that could not be done using conventional equipment due to the massive power requirements associated with heating the entire part at the same time or very large diameter gears that will not fit inside any existing carburizing furnaces. To harden a tooth root the coil rests in between to adjacent teeth. This configuration hardens the tooth root and the flank of each adjacent tooth as shown in Figure 8. This method of hardening provides strength and wear resistance on the contact areas of the gear while minimizing dimensional movement by leaving the tooth tips unhardened. Conclusion A variety of heat treatment techniques exist for case hardening gears. Heat treatment processes can be tailored to maximize the life and optimize the performance of a gear in its service application by tailoring the heat treatment to produce specific desired properties. Distortion is always a factor in heat treatment processes, but it can be controlled and minimized by selecting specific processing parameters, being knowledgeable about fixturing, using different types of case hardening processes, and taking extra steps to ensure the gears have minimal stresses present in them prior to heat treatment that could be relieved. No one heat treat process is superior to the other, but ultimately they all compliment each other. Having an understanding of the processes available will help you choose which process is appropriate for your gear. At the turn of the 20th century, the use of molten salt as a heating and quenching medium for steels was developed in England. It rapidly came into use in Europe as a low-cost method of heat treating. Equipment was inexpensive, and molten salt provided a reproducible method of heat treatment. In this short article I will review the types of salts used for heat treating and some hazards associated with molten salt heat treatment. Advantages of Molten Salt Heat Treating Parts that are heated in salt baths are heated by conduction. The thermal mass of the molten salt provides a large thermal source for heating of parts. Heating of parts in a salt bath is much more rapid than in air or atmosphere furnace. The heat-up of the parts is only limited by the thermal conductivity of the part. Since metals have high thermal conductivity, the core of the part lags the surface by only a small amount. A 25 mm diameter of steel would require four minutes to reach the austenitizing temperature, while it would take 30 minutes or more in a standard radiation furnace [1]. Salt bath furnaces are efficient at heating parts, with more than 90 percent of the heat applied to the furnace going directly to the part. Atmosphere furnaces are approximately 60 percent efficient. Temperature uniformity is excellent, with uniformity less than ± 3°C throughout the bath. When parts are heat treated in a molten salt, they are completely immersed. Surface protection from the salt can reduce decarburization and the formation of scale. Quenching in a molten salt can reduce distortion. Since heat transfer is by conduction, a much more uniform heat transfer occurs across the surface of the part. Further, due to buoyancy effects, sagging of parts during heat treating is minimized. Parts that are heated in salt baths are heated by conduction. The thermal mass of the molten salt provides a large thermal source for heating of parts. Types of Salts – Salt Composition There are several different types of heat-treating operations that can be performed in molten salts. The first is to solution heat treat the part (austenitize in steel) to bring it to the desired temperature. The second operation is to quench the part in the molten salt as part of martempering operation or austempering. Lastly, there is the tempering or aging operation (non-ferrous alloys). All these unit operations can be performed in a molten salt. There are also specialized salts used for carburizing or nitriding operations. These usually contain a form of sodium cyanide or cyanate. These salts will be mentioned briefly, as their use has significantly declined due to environmental and safety considerations. Molten salts can be used at a temperature range of 150°C to 1,287°C (300°F to 2,350°F). Molten salts are divided into three temperature ranges, with characteristic chemistry. The ranges are low temperature (150° – 620°C); medium temperature (650° – 982°C); and high temperature (982°C – 1,287°C) molten salts. Low Temperature (150°–620°C) Low temperature salts are used for a wide variety of unit operations, such as solution heat treating of aluminum, or martempering and austempering of steels. They are usually mixtures of various nitrates and nitrates of sodium and potassium. These salts are completely molten at 150°C. Some salts, used for energy storage in solar applications, are molten at 121°C (250°F. These salts contain up to 25 percent lithium nitrate. There are no known heat-treating applications using lithium nitrate as a component of the low temperature salt due to the high cost of lithium salts. Use of these mixtures of nitrate/nitrite baths at temperatures above 620°C is not recommended. These baths are unstable above 620°C, and a strong exothermic reaction can result. This is particularly true when in contact with aluminum. Table 1: Molten salt classifications per MIL-S-10699B [6]. Medium Temperature (650°–982°C) Since nitrates and nitrites are unstable at temperatures above 620°C, another type of molten salt chemistry is required. Molten salts in this class of salts are mixtures of sodium chloride (NaCl), potassium chloride (KCl), calcium chloride ($CaCl_2$), sodium carbonate (Na_2CO_3), and barium chloride ($BaCl_2$). At lower temperatures within the operating range, the composition would be primarily potassium chloride and sodium carbonate. At the top end of the range, barium chloride would be the primary constituent. For most general-purpose heat treating to 900°C, a 50/50 mix of sodium chloride and potassium chloride is the most common. This avoids any environmental or disposal issues with barium salts. While these salts are neutral to steel, they will decarburize steels as the salts oxidize. As temperature is increased, the salts will tend to oxidize more rapidly. Initially, the chlorides form oxides in the form of Na_2O or K_2O. This occurs due to the presence of air at the liquid interface. Formation of sodium carbonate eventually occurs, with further increases in decarburization. The use of a rectifier, such as borax, boric acid, silicon carbide, or ammonium chloride [2], added to the bath can restore the neutral character of the bath. Previously, methyl chloride was used as a rectifier, by bubbling the methyl chloride through the bath [3]. However, due to health and safety concerns, the use of methyl chloride has largely been discouraged. High Temperature (982°C–1287°C) The high temperature molten salt baths are predominately barium chloride, with either potassium chloride or sodium chloride added to the composition. However, the most common bath is barium chloride with a small amount (up to 5 percent) of silica added as a bath rectifier. Specialized Salts – Nitriding and Carburizing There are also specialized salts for molten salt carburizing and nitriding, as well as salts for blackening or bluing steels. In carburizing molten salts, the salts consist of a mixture of barium chloride and sodium cyanide. Concentration of sodium cyanide is on the order of 30-35 percent [4]. Temperatures used are like those used in atmosphere carburizing (850° to 950°C). The depth of carburizing is generally low at 0.5 mm. Because of the relatively shallow carburizing depths, the corresponding time at temperature is short. The concentration of the sodium cyanide can be increased if the depth of carburized case is deeper. Since the cyanide is the source of carburizing, it will deplete over time. To prevent depletion, a cover of carbon is usually added. This prevents oxidation of the cyanide and prevents radiation heat losses. Typical drag-out of about 6 percent means that fresh salt must be added daily. Obviously, the presence of sodium cyanide can be a serious health and environmental problem if the necessary steps are not taken to mitigate possible release of hydrogen cyanide. Cyanides will decompose in a bath to carbonates [5]. Some hydrogen cyanide may be produced during this decomposition. Therefore, it is necessary that strong mechanical exhaust be used [5]. The storage of any sort of acids should be prohibited from areas where the carburizing salt is stored. If there are acids used in the production process, such as pickling, it is critical that the parts are thoroughly washed and rinsed prior to the acid-containing process. Mechanical ventilation is strongly recommended. The cyanide wastes (used salt or contaminated rinse water) must be chemically decomposed before they are disposed. Decomposition is usually done by treating the salt in aqueous solution with an oxidizing agent such as sodium hypochlorite [5]. Strong ventilation is required. Conclusions In this column, the advantages of the use of molten salt were illustrated. The salt composition of the various temperature ranges of salt were explained. In later columns, the application of molten salt quenching (martempering and austempering) will be discussed. As always, should you have any comments or questions regarding this column, please contact the editor or myself. References W. J. Laird, "Salt Bath Equipment," in ASM Handbook 4: Heat Treating, Metals Park, OH, ASM International, 1991, pp. 475 – 483. R. W. Foreman, "Pelletized Rectifier for Molten Neutral Salt Baths and Method". USA Patent 4,009,112, 22 February 1977. P. H. Kramer, "Method of Rectifying a Neutral Molten Salt Treating Bath". USA Patent 2,474,680, 28 June 1949. H. Solakain, "Salt baths and Salt Bath Furnaces," Metal Treating, no. January-February, pp. 3-8, 1958. Park Thermal International, Inc., "A Guide to the Safe Use of Molten Salt Baths," Park Thermal International, Inc., Georgetown, ON Canada, 1996. "MIL-S-10699B, Military Specification: Salt, Heat Treating (for Metals)," 1977.