

Heat Treatment of Metals: Change Metal Characteristics

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ABSTRACT:

Metals must undergo heat treatment during the production and processing stages to improve their mechanical characteristics, change their microstructure, and increase their overall performance. Acquire certain desired qualities, it entails carefully heating and cooling metal alloys. The chapter explains the essential ideas and methods of heat treatment, along with all of the steps that go into it. To obtain the required material qualities, it emphasizes the need of managing heating and cooling rates in addition to temperature and time factors. The overview also highlights the many heat treatment techniques that are often used, including annealing, tempering, quenching, and precipitation hardening. Each technique has certain goals and impacts on the microstructure and characteristics of the metal. The chapter ends by recognizing the extensive use of heat treatment in a variety of sectors, including the construction, aerospace, and automotive industries. It underlines how crucial it is to optimize the heat treatment procedure to obtain the necessary material qualities while taking into account elements like cost, time, and energy efficiency.

KEYWORDS:

Annealing, Cooling, Hardness, Heating, Hardening, Material.

I. INTRODUCTION

In the discipline of metallurgy, heat treatment is a crucial procedure that modifies the characteristics of metals by putting them through carefully regulated heating and cooling cycles. It is a tried-and-true method that has been used for centuries to improve the mechanical, physical, and occasionally even chemical properties of different metal alloys. Metals must be heated throughout the manufacturing and processing processes to alter their microstructure, enhance their mechanical properties, and improve their overall performance. It requires carefully heating and cooling metal alloys to get specific desirable properties. The main principles and techniques of heat treatment, as well as each step involved, are explained in the chapter. It highlights the necessity of controlling heating and cooling rates in addition to temperature and time considerations to acquire the necessary material properties [1], [2].

The review also emphasizes the several frequently employed heat treatment methods, including precipitation hardening, annealing, tempering, and quenching. Each method has certain objectives and effects on the metal's microstructure and properties. The chapter concludes by emphasizing the widespread application of heat treatment in several industries, including the building, aerospace, and automotive sectors. It emphasizes how important it is to optimize the heat treatment process while taking into account factors like cost, time, and energy efficiency to acquire the required material attributes. Heat treatment's main goals are to change the structure of the metal, raise its mechanical strength, increase its hardness or ductility, improve its machinability, alleviate internal tensions, and obtain the material qualities that are sought for particular applications. To create notable changes in the metal's microstructure and characteristics, metallurgists must carefully regulate the process' temperature, duration, and cooling rate [3], [4].

Heating, soaking, and chilling are the three basic steps in the procedure. The alloy's composition and the intended result define the initial temperature at which the metal is heated. Several techniques, including flames, induction heating, and furnaces, can be used to conduct the heating. The metal is heated to the correct temperature and maintained there for a specific amount of time to allow the metal's microstructure to completely change. This process, often referred to as soaking or holding, makes sure that the heat permeates the material evenly. Depending on the intended effect, the metal is either swiftly cooled after the soaking period or occasionally gently chilled. The pace of cooling can have a big impact on the metal's final characteristics. To accomplish certain qualities, many cooling techniques can be used, including controlled furnace cooling, oil quenching, water quenching, and air cooling.

The industry uses a variety of heat treatment procedures, each with its own goals and methods. Processes including annealing, tempering, quenching, normalizing, and case hardening are frequently used. The kind of metal required qualities, and intended application are taken into consideration when choosing a procedure because each has a distinct function. All things considered, heat treatment is a crucial metallurgical procedure that allows for the optimization of metal characteristics, making it a foundational process in materials engineering. It makes it possible to create materials with specialized properties, enhanced functionality, and prolonged lifespan, enabling the creation of high-quality components for a variety of sectors, including automotive, aerospace, building, and manufacturing. To increase metals' overall performance, change their microstructure, and improve their mechanical characteristics, heat treatment is a vital step in the manufacture and processing of metals. It entails carefully heating and cooling metal alloys to produce a desired set of properties [5], [6].

The chapter outlines the core theories and methods of heat treatment, as well as the numerous steps that make up the procedure. It emphasizes how crucial it is to regulate heating and cooling rates together with temperature and time constraints to obtain the desired material qualities. The many heat treatment techniques that are often used, including annealing, tempering, quenching, and precipitation hardening, are also highlighted in the chapter. Each technique has certain goals and impacts on the metal's microstructure and characteristics. The chapter also discusses how important it is to comprehend phase diagrams and how alloys change following heat treatment. The material's structure may be changed thanks to this information, allowing for the production of desired phases or the deletion of undesirable ones. The chapter comes to a close by noting the extensive use of heat treatment in several fields, including building, aerospace, and automotive. To attain the specified material qualities, the heat treatment process must be optimized while taking into account variables like cost, time, and energy efficiency. The summary of heat treatment of metals in the chapter emphasizes its relevance in changing and enhancing the characteristics of metal alloys for various industrial purposes [7], [8].

II. DISCUSSION

Annealing

A heat-treatment procedure called annealing is used to soften metals, relieve internal tensions, enhance the material's ductility, and improve machinability. It entails heating a metal or alloy to a specified temperature, maintaining it there for a lengthy time, and then carefully cooling it. The primary goals of annealing are to improve the metal's microstructure, remove any structural flaws or blemishes, and lessen hardness. It is especially helpful for materials that have gone through cold-working procedures that might cause strain hardening and dislocations, such as rolling, forging, or drawing. The metal is heated during annealing to a temperature that is higher than its recrystallization temperature but lower than its melting point. The structure of the metal can be recovered and recrystallized in this temperature range. A more uniform and equiaxed structure is created during the recrystallization process, which reduces internal stresses and increases the ductility of the material. In order to guarantee that the heat enters the metal evenly during annealing, the length of the soaking or holding period is crucial. The amount of time needed varies according to the material's makeup, thickness, and goal. From a few minutes to several hours or even days, it might last.

The metal is then carefully cooled to room temperature following the soaking phase, frequently in a furnace or by burying in insulating material to guarantee regulated cooling. This progressive cooling preserves the proper microstructure and helps to stop the material from developing additional stresses or flaws. Depending on the particular needs, annealing can be carried out using a variety of processes. Full annealing, stress-relieving annealing, and recrystallization annealing are a few typical varieties. To provide the intended effects, each kind has its temperature range, soaking period, and cooling pace. Full annealing entails slowly cooling the material in a furnace after raising the temperature just slightly over its critical range. It creates a softer, more machinable material that is ductile and soft. To release lingering tensions in the material without significantly expanding the grain size, stress-relieving annealing is carried out at a lower temperature. After cold working procedures, recrystallization annealing is used to improve the material's ductility and polish the grain structure. Many different sectors, including industrial, automotive, aerospace, and electronics, employ annealing extensively. Improved mental workability and formability, decreased brittleness, and consistent material characteristics are all achieved through this crucial process, which eventually results in high-quality finished products.

Martensite Formation in Steel

A key occurrence during the heat treatment of steel is the production of martensite. A highly trained and supersaturated solid solution of carbon in iron defines it as a metastable phase. Martensite is unusual in that it has high levels of hardness and strength, which makes it useful for some uses. The quenching process, which

involves fast cooling, causes martensite to develop in steel. Quenching is the process of rapidly bringing steel from a high temperature, usually over its critical temperature, to room temperature or below. The carbon is retained in a supersaturated solid solution as a result of the high cooling rate that precludes carbon atom diffusion. The microstructure of the steel changes during quenching from the original austenite phase to martensite. High temperatures result in the face-centered cubic FCC crystal structure of austenite. The carbon atoms are trapped in the iron lattice as the steel cools quickly, distorting the crystal structure. Because there is no atomic diffusion during the transition from austenite to martensite, the process is characterized as a diffusionless transformation. Instead, it uses a displacive process in which the carbon atoms shear or rearrange the iron lattice to create a crystal structure known as a body-centered tetragonal BCT. A very stressed and internally strained material is produced as a result of this transition.

The supersaturated carbon can be locked in the deformed crystal structure of martensite due to the high cooling rate experienced during quenching, which hinders the development of equilibrium phases. The martensitic steel's improved hardness and strength are a result of its high carbon content. The quantity of martensite that forms in the steel is influenced by several aspects, including the carbon concentration, alloying components, cooling rate, and original austenite's chemical makeup. Greater martensite formation is favored by higher carbon concentration and quicker cooling rates. The production and stability of martensite in steel can also be influenced by alloying substances like chromium and molybdenum.

The quenched steel can go through additional heat treatment procedures, such as tempering, to acquire specified mechanical qualities. The martensitic steel is heated to a certain temperature range, then cooled gradually to complete the tempering process. This procedure aids in reducing the martensite's brittleness and internal stresses, producing a more ductile material with the necessary hardness and toughness. To attain a variety of mechanical qualities, including high hardness, strength, and wear resistance, martensite production is a crucial process that is used in steel. It has uses in many different fields, such as the production of tools and dies, automotive parts, cutlery, and structural steels, where hardness and strength are crucial criteria.

The Heat Treatment Process

Metals and alloys are subjected to a series of carefully regulated heating and cooling operations throughout the heat treatment process to change their microstructure and, as a result, their mechanical and physical characteristics. Depending on the intended result and the type of material being treated, several procedures and methods may be employed during heat treatment. The following steps are often included in the overall heat treatment procedure, though:

Heating

Temperature-specific heating is applied to the metal or alloy. Flames, induction heating, furnaces, and other techniques can all be used for heating. The temperature is carefully chosen based on the makeup of the material and the intended result. Heating is used to speed up phase changes, dissolve solute atoms, and encourage diffusion.

To hold or to soak

The metal is kept at the desired temperature for a long enough time once it has been attained. Soaking or holding time is the term for this phase. The amount of time spent soaking enables the material to undergo the appropriate modifications and experience homogeneous atom diffusion. Depending on the material and the precise heat treatment procedure, the soaking duration might vary from a few minutes to many hours or even days.

Cooling

The metal is cooled down at a regulated rate to room temperature or another temperature after the necessary soaking period. A crucial element that can have a big impact on the final microstructure and material characteristics is the cooling rate. To accomplish certain qualities, several cooling techniques, such as controlled furnace cooling, oil quenching, water quenching, and air cooling, may be used.

Other Procedures

The heat-treated material may go through further procedures based on the intended result. These procedures could involve carburizing, annealing, quenching, normalizing, or precipitation hardening. Each procedure accomplishes a certain goal and aids in the production of specific material traits or features.

Tempering

In this procedure, the material is heated to a particular temperature below its lower critical temperature, and then it is controlled-cooled. It is carried out to obtain the necessary strength and ductility, decrease the hardness and brittleness of quenched materials, and enhance toughness.

Annealing

In the heat treatment procedure of annealing, the material is heated to a certain temperature and maintained there for a long time before being slowly cooled. It is used to improve machinability, reduce internal tensions, soften the material, and increase its ductility.

Quenching

Austenite has converted into the hard and brittle phase martensite by the quick cooling process known as quenching. It includes rapidly chilling the material to maintain a supersaturated solid solution, leading to an improvement in hardness and strength.

Normalizing

Similar to annealing, normalizing is a heat-treating procedure that uses air cooling rather than gradual cooling. It is applied to increase machinability, establish homogeneous mechanical characteristics across the material, and refine the grain structure.

Precipitation Hardening

Certain alloys that, when aged at high temperatures, may develop a fine dispersion of precipitates are subjected to this technique. The material gains more hardness and strength as a result of the precipitation hardening process.

Carburizing

Low-carbon steels can have their surface layer added with carbon by the surface heat treatment technique known as carburizing. This increases hardness and wear resistance by creating a surface layer with a high carbon content. Overall, the metallurgical process of heat treatment is a flexible and significant tool that enables the modification of material characteristics to satisfy particular application needs. It has a big impact on sectors including manufacturing, aerospace, automotive, and construction where controlling the characteristics of materials is crucial to producing high-quality, high-performing products.

Hardenability

A steel or alloy's capacity to be toughened by heat treatment procedures, notably through the production of martensite, is referred to as hardenability. It is a crucial characteristic that governs how uniformly and deeply a material may obtain hardness.

The chemical makeup of steel, namely the alloying elements present, plays a major role in determining how hardenable it is. Carbon, chromium, molybdenum, nickel, and manganese are only a few of the substances that have a big impact on hardenability. Higher carbon content often enhances hardenability by increasing the quantity of carbon accessible for martensite formation. By generating carbides or other strengthening phases, alloying elements like chromium, molybdenum, and nickel can also improve the hardenability of materials. Several techniques, including the Jominy end-quench test and the use of hardness profiles, are frequently used to assess hardenability. In the Jominy test, a cylindrical specimen is heated to a certain temperature, then one end is rapidly quenched by spraying water on it while the other end cools gradually. The hardenability of the material is shown by the ensuing hardness profile along the specimen's length.

A hardenability curve or a Jominy hardenability diagram is frequently used to illustrate the hardenability of steel. These graphs illustrate the connection between the cooling rate and the development of martensite or the consequent hardness at different distances from the quenched end of the specimen. The curve shows the minimum rate of cooling necessary to reach a certain hardness or martensite content. The manufacturing of components with constant hardness and strength is possible because of the great cross-sectional hardenability of steels. However, steels with limited hardenability only show hardness near the quenched surface, which restricts their use in applications requiring a uniform distribution of hardness.

Hardenability is a crucial factor to take into account when choosing materials and performing heat treatment on them. To attain the necessary hardness and mechanical qualities, it aids in determining the right cooling rate and

quenching medium. For applications like tools, gears, and certain structural components where high strength, wear resistance, and hardness are required, steels with high hardenability are frequently used. Engineers and metallurgists can choose the best alloy compositions and optimize heat treatment procedures by taking into account the hardenability of steel to provide the needed material qualities for particular applications.

Precipitation Hardening

Precipitation hardening, also known as age hardening, solution, and aging treatment, or simply age hardening, is a heat-treating procedure used to improve the strength and hardness of various alloys, most notably aluminum, copper, and some varieties of stainless steel. To cause the precipitation of finely distributed particles inside the material's microstructure, the procedure entails a series of heating, quenching, and aging processes. The following phases commonly make up the precipitation hardening process:

Solution Therapy: The alloying components dissolve into the matrix at a high temperature known as the solutionizing temperature, forming a solid solution. This high-temperature procedure helps homogenize the alloy composition by dissolving any soluble alloying components or impurities. To avoid the production of massive precipitates, the material is then immediately quenched.

Aging: Following quenching, the material is exposed for a predetermined amount of time to a lower temperature known as the aging temperature. The alloying components progressively develop tiny, coherent precipitates inside the microstructure throughout this aging period. These precipitates increase the strength and hardness of the material by acting as barriers to the migration of dislocations. Depending on the alloy and the required qualities, the age period might range from a few hours to several days.

Precipitate Hardening and Growth

The precipitates continue to increase in size and quantity as the aging process goes on, reinforcing the material as a result. By changing the aging time and temperature, the precipitates' development and distribution may be managed. The creation of a uniform distribution of finely dispersed precipitates is made possible by suitable precipitation hardening treatment, improving the mechanical characteristics. Precipitates and crystallographic dislocations in the material interact to provide the strengthening process in precipitation-hardened alloys. The dislocations' mobility is impeded by the fine precipitates, which increases their strength and hardness. Regarding the characteristics of materials, precipitation hardening has several benefits. High strength may be developed while yet retaining good toughness and corrosion resistance.

Additionally, it offers the option to customize the material's properties, making it appropriate for a variety of applications where a blend of strength, hardness, and other particular qualities is required. Precipitation hardening may occur in a variety of alloys, such as aluminum alloys such as 6061 and 7075, copper alloys such as beryllium copper, and certain stainless steels such as 17-4 PH stainless steel. These alloys are used in fields where high strength, low weight, and durability are crucial, including aerospace, automotive, defense, and sports products. By causing the precipitation of finely distributed particles by carefully regulated heating, quenching, and aging, precipitation hardening is a heat treatment technique used to increase the strength and hardness of certain alloys. It has the benefit of allowing material qualities to be adjusted to match particular application needs, producing high-performance materials.

Surface Hardening

Surface hardening is a heat-treatment technique used to improve a material's surface layer's hardness and wear resistance while preserving the inner layer's toughness and flexibility. Although other materials, such as cast iron and some non-ferrous alloys, can also go through surface hardening, it is typically used with low-carbon and alloy steels. There are several surface hardening techniques, each having benefits and applicability for certain purposes. The typical methods include:

Carburizing Case Hardening

By exposing low-carbon steel to a carbon-rich environment, such as a carbonaceous gas or a solid carbon source, carburizing entails adding carbon to the surface layer of the metal. A high-carbon layer called the case is created when the carbon atoms infiltrate into the surface. To obtain the necessary mix of hardness and toughness, this case is subsequently quenched, hardened, and finally tempered.

Nitriding

In the nitriding process, nitrogen is added to the steel's surface to create a coating of hard compound steel. The steel is heated in a salt solution that is high in nitrogen or an ammonia gas environment. Hard nitride compounds are created when the nitrogen atoms permeate through the surface and interact with certain alloying components. Nitriding increases wear resistance and surface hardness while preserving the material's inner toughness.

Hardening by Induction

High-frequency induction heating is used in induction hardening to target-heat the steel component's surface. After the targeted heating, the area is quickly cooled, usually with water or polymer-based quenchers. The surface of the material becomes harder as a result of this process, but the core is mostly unaffected. Gears, shafts, and camshafts are examples of complex-shaped components that frequently undergo induction hardening.

Burning Hardening

With flame hardening, the surface is heated locally using a high-temperature flame, such as oxy-acetylene or oxy-propane. The heated region is then quickly cooled and the top layer is hardened by quenching, which is typically done with water spray or jets. For big or atypically formed components, such as large gears and tools, flame hardening is frequently used.

Laser Hardening

A powerful laser beam is used to heat and harden the material's surface in the precise surface-hardening technique known as laser hardening. The targeted region is heated quickly by the laser beam before being quenched in a variety of ways. Laser hardening is appropriate for complicated geometries and tiny regions because it enables localized and selective hardening. The goal of surface hardening techniques is to create a hardened outside while preserving a robust and ductile inside. In applications involving abrasive wear, impact, or high contact pressures, the hardened surface increases wear resistance, lowers friction, and lengthens the component's lifespan. In sectors including automotive, aerospace, tool manufacture, and mining where parts are subjected to abrasive working conditions, surface hardening procedures are frequently utilized. The proper surface hardening technique should be chosen based on the application-specific requirements, intended hardness, component shape, and material composition.

III. CONCLUSION

Metals and alloys can have their properties changed by heat treatment, which improves the mechanical, physical, and chemical qualities of the metals and alloys. To create the appropriate microstructures and characteristics, a controlled heating, soaking, and cooling procedure is used. Depending on the intended outcome and the material being treated, several heat treatment processes, including annealing, quenching, tempering, normalizing, and precipitation hardening, are used. While quenching and tempering are used to improve hardness and strength, annealing is used to soften the material and relieve internal tensions. Normalization improves the grain structure, while precipitation hardening increases strength by causing precipitates to develop. Heat treatment efficiency depends on several variables, including heating temperature, soaking duration, cooling rate, and the presence of alloying materials. The hardness, strength, toughness, and wear resistance of materials may all be customized thanks to the management of these factors. Processes for heat treatment are essential in several sectors, including industrial, aerospace, automotive, and construction. They make it possible to produce materials and parts of the highest caliber that function better. Structures, tools, gears, bearings, springs, and many other crucial pieces all use heat-treated metals.

REFERENCES

- [1] X. Yan, Y. X. Xu, Y. Wu, en H. Lin, Effects of heat treatment on metal-ceramic combination of selective-laser-melted cobalt-chromium alloy, *J. Prosthet. Dent.*, 2018, doi: 10.1016/j.prosdent.2018.05.012.
- [2] V. Ivaschenko, G. Shvachych, M. Sazonova, O. Zaporozhchenko, en V. Khristyan, METALS HEAT TREATMENT MODEL, *Mod. Probl. Metal.*, 2020, doi: 10.34185/1991-7848.2020.01.05.
- [3] V. Kotlan, R. Hamar, D. Pánek, en I. Doležel, Combined heat treatment of metal materials, *COMPEL - Int. J. Comput. Math. Electr. Electron. Eng.*, 2016, doi: 10.1108/COMPEL-08-2015-0302.
- [4] A. Nirala et al., Fabrication of a tubular furnace for sintering and heat treatment of metals/alloys, 2020. doi: 10.1016/j.matpr.2020.04.222.
- [5] W. H. Wu, Q. P. Wang, Y. J. Li, en J. S. Zhang, Quantitative analysis upon fund-sponsored dissertations in Heat Treatment of Metals during 2006-2009, *Jinshu Rechuli/Heat Treat. Met.*, 2010.
- [6] Headquarters Department of the Army, Properties, Identification, & Heat Treatment of Metals, US Army - Fundam.

Mach. Tools TC 9-524, 1996.

- [7] G. Wu et al., Synthesis-structure-performance correlation for polyaniline-Me-C non-precious metal cathode catalysts for oxygen reduction in fuel cells, *J. Mater. Chem.*, 2011, doi: 10.1039/c0jm03613g.
- [8] P. Kürnsteiner, M. B. Wilms, A. Weisheit, P. Barriobero-Vila, E. A. Jägler, and D. Raabe, Massive nanoprecipitation in an Fe-19Ni-xAl maraging steel triggered by the intrinsic heat treatment during laser metal deposition, *Acta Mater.*, 2017, doi: 10.1016/j.actamat.2017.02.069.