

Heat Treatment

INDUSTRY

A Glossary of Terms

Technical Note

Heat Treatment Definition

Heat Treatment can be defined as a combination of heating and cooling operations applied to metals and alloys in the solid state to obtain desired conditions or properties.

The Heat Treatment of metals involves raising the temperature of a steel or alloy, often through a prescribed thermal profile to a defined temperature. The material is then held at temperature for a period of time before being cooled usually at a carefully controlled rate or in a quench process to a fixed temperature or to ambient temperature.

Treatments are carried out in furnaces and ovens where gases are often used to control the atmosphere of the process.

Controlled atmospheres are used to reduce the effects of oxidation on the component being treated or to provide an enriching atmosphere for surface chemistry effects.

Heat treatments can be employed to homogenise cast metal alloys or to improve their hot workability, to soften metals prior to, and during hot and cold processing operations, or to alter their microstructure in such a way as to achieve the desired mechanical properties.

Thermal treatments of metallic alloys are also employed to alter the surface chemistry of a material. This is achieved by diffusing Carbon, Nitrogen and other gaseous or solid material in to the surface of the component.

These processes are used to give defined surface hardness and to improve wear, corrosion and fatigue resistance.

Thermal Treatments can be classified by their purpose

Heat Treatments, which modify the microstructure of the material or change the phase structure to improve the mechanical properties for specific applications or further work processes.

Annealing

A term used to describe a variety of softening heat treatments by changing the microstructure of an alloy.

Used mainly to remove stresses, to alter ductility, to induce softness or to produce amongst other things a defined crystalline grain structure.

Various degrees of annealing occur by slow cooling an alloy, which has been heated to temperatures between 0.3 and 0.5 of its melt temperature.

Homogenisation

Primarily used to equalise temperature in stock material prior to hot working, or to reduce excessive coring, which can occur in ingots and continuously cast alloys.

Coring

Non uniformity of the chemical composition of cast stock.

Stringers

Small quantities of impurity that align into long threads (stringers) on rolling. These threads restrict grain movement so providing improved creep-strength.

Stress Relieving

A process used to remove stresses in welded, rapidly cooled components or cold work products. Relief is achieved by heat treating the component at a temperature for a period of time and then slowly cooling the product back

to room temperature. The time and temperature are alloy dependent.

Normalising

A treatment used to remove undesired microstructure effects of previous heat treatments and performed to produce a uniform grain structure.

Hardening

One of a number of processes used to improve the hardness of an alloy superior to that normally present in the core stock. Usually achieved by quenching material from above its upper critical temperature.

Solution Heat Treatment

A process in which certain alloys mainly some stainless steels and copper based alloys are heated to a suitable temperature to allow the constituents to enter into solid solution. The process is then held at the defined temperature for a specified length of time dependent on the alloy mix to allow the various components to form a coherent solid but soluble mass before rapid cooling (precipitation)

The material is then said to be in a supersaturated, unstable state, and may subsequently exhibit age hardening.

Precipitation Hardening (Age Hardening)

A process in which the hardness and stress-rupture strength can be improved of hardenable high-temperature steels, as well as titanium and nickel and cobalt alloys. The process consists of a solution heat treatment followed by aging during which the constituents of the structure form a solid solution that is frozen during rapid cooling. The hardness increase is caused by the aging cycle.

Age hardening (Precipitation Hardening)

A process in which certain nonferrous and ferrous alloys are heated, quenched, and then aged at a relatively low temperature above room temperature, to allow precipitation hardening to occur. This can significantly increase work-piece strength without any affect on work-piece ductility. The hardening process can be halted by refrigeration of the component.

Quench hardening

The objective of this treatment is to produce a fully Martensitic micro-structure in the steel.

To achieve this the steel must be cooled rapidly from the austenitic condition.

The process is suitable for ferrous metal and alloys in which steel and cast iron alloys are heated above a certain critical temperature and rapidly cooled to produce a hardened structure. Either surface hardening or full-hardening can result, depending on the cooling rate. The process requires close control of temperature during heating and quenching.

One draw back from the fast cooling rate required to produce Martensite is that the outer surface is cooled more quickly than the core and thin/thick sections respond at different rates. This may result in distortion or cracking of the component.

When the quenching rate is insufficient or the section size is too large or the steel had insufficient hardenability Bainite is formed instead of Martensite.

Whether Bainite or Matensite is formed during the quench process the material is usually tempered before use.

In the case of Bainite the process is usually used to reduce internal stresses whereas in Matensite it is to improve ductility and toughness at the expense of strength and hardness.

Tempering

A treatment used to remove brittleness from mainly quench hardened steels and achieved by thoroughly soaking the material at an alloy dependent temperature prior to cooling.

Also referred to as the Draw process.

Martempering

To overcome the restrictions of conventional quenching and tempering, martempering can be used. The process, sometimes referred to as marquenching permits the transformation of Austenite to Martensite to take place at the same time throughout the structure of the metal part. This is achieved by interrupting the quench cycle, the cooling is stopped at a point above the Martensite transformation region to allow sufficient time for the centre to cool to the same temperature as the surface. Then cooling is continued through the Martensite region, followed by the usual tempering.

Austempering

This is another process that can be used to overcome the restrictions of conventional quench and tempering. The quench is interrupted at a higher temperature than for Martempering to allow the metal at the centre of the part to reach the same temperature as the surface. By maintaining that temperature, both the centre and the surface are allowed to transform to Bainite and are then cooled to room temperature.

Advantages of austempering are, less distortion and cracking than Martempering, No need for final tempering, Improvement of toughness and improved ductility.

Case Hardening

One of a number of heat treatment processes which improve the surface hardness of a steel alloy without affecting the properties of the core material.

Flame Hardening

A localised hardening process where components are subject to mainly an acetylene flame and then spray quenched.

Induction Hardening

A widely used process particularly in the automotive and tools market for the surface hardening of steel. The components are heated by means of an induction set which applies an alternating magnetic field to the work-piece.

The temperature of the components increases to the transformation range or just above before being immediate quenched. The physical properties of the core material remain unaffected by the process.

Steel

An alloy of iron, carbon and often other elements. The amount of carbon is below 2% by mass. Steels in which carbon is the main alloying element are termed carbon steels. Those with significant concentrations of other elements are termed alloy steels

Wrought iron contains less than 0.035 percent carbon. This high purity ensures good corrosion resistance. In structure it is classed as ferrite, but contains a little slag elongated into stringers by rolling. This reduces its strength and malleability.

Micro Structure States

Heat treatments are used to change the micro structural state of steels and alloys.

Each of the states holds advantages in different applications and metals may be produced which exhibit combinations of the states

The principle transformations are as follows.

Austenite

A solid carbon/iron state with defined microstructure, which occurs in alloys when they are heated to a value range above its upper critical temperature. The Austenising temperature is dependent on the alloy type and grade of material.

Austenite is one of the allotropes of iron, also known as gamma iron. It is formed when iron is between 912°C and 1,394°C and has a face-centred cubic structure. The structure is also found in carbon steel.

Pearlite

A lamellar constituent of steel consisting of alternate layers of ferrite (alpha-iron) and cementite (iron Carbide Fe₃C) and is formed on cooling austenite at 727°C. This produces a tough structure and is responsible for the mechanical properties of unhardened steel.

When steel is cooled at the rate of about 400°C per minute austenite crystals change into pearlite (a fine lamellar structure of alternating platelets of ferrite and iron carbide) at about 727°C.

Faster cooling produces Martensite.

Bainite

A non-equilibrium phase, usually in steel, which is formed by quenching from the austenite phase. The rate of quenching required is slower than that necessary to form Martensite but faster than that which produce the equilibrium phase of Pearlite. Two types of Bainite are recognised; upper and lower. Upper Bainite forms at higher temperature and consequently the carbon present has sufficient to diffuse out forming carbides outside the bainite laths. Lower bainite forms at lower temperature and contains carbides within the laths as the carbon cannot diffuse out rapidly enough.

Martensite

Very rapid cooling (quenching) of steel (at about 1,000°C per minute) produces a new microstructure, Martensite. It is the hardest and most brittle form of steel. Subsequent reheating to about 400°C and holding it for a time (tempering) produces a strong and tough steel with lower hardness and brittleness.

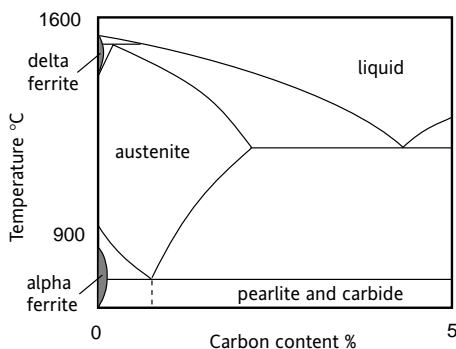
Ferrite

Ferrite, is a condition in iron that has a number of inherent properties at room temperature such as a large grain size, low hardness, good ductility and is easily machined.

The ferrite condition exists in a particular crystal form and will exist at low temperatures. Iron is therefore made up of millions of tiny crystals. The crystals are bound together in what is called a lattice structure.

Pure iron up to 912°C has a body centred cubic structure and is known as alpha ferrite. Between 1394°C and the melting point of iron the bcc structure is now known as delta ferrite. Also found in carbon steel.

Phase diagram showing typical transformation regions



Cementite

Iron carbide, Fe₃C. Harder and stronger than ferrite, but not as malleable.

Treatments, which alter the surface chemistry of an alloy

Typically Carburising, Nitriding, Carbonitriding and Nitrocarburising

In these processes the surface layers of the alloy are hardened and strengthened by subjecting the component to an enriched gaseous atmosphere of carbon or nitrogen whilst the material is taken through an elevated thermal profile.

Similar material properties containing other surface molecular components can be obtained in processes such as Ion Implantation - Chemical Vapour Deposition (CVD), Physical Vapour Deposition (PVD), Boriding and Diffusion Alloying Aluminising, Salt Baths.

Carburising

Various processes that add carbon to the surface of steel to improve case hardness and surface wear resistance.

The results of the carburising process is to produce an effective case depth of hardness which enable components manufactured from Low-carbon alloy - case-hardening steels to be used in applications which demand greater wear characteristics.

Gas Carburising

A surface chemistry process, which improves the hardness of a component by diffusing carbon, into the surface layer to improve wear and fatigue resistance.

The work pieces are held at an elevated temperature and are subject to an enriched carbon potential atmosphere such that nascent carbon atoms can diffuse in to the surface layers of the component. The process is usually carried out in a combined sealed atmosphere quench furnace where components are immediately quenched after the diffusion process.

The conditions for producing a carbon potential atmosphere are generated by adding enrichment gas (often methane CH₄ or Dilution air on top of an endothermic carrier gas which may consist of 40% Nitrogen - 40% Hydrogen - 20% Carbon Monoxide (CO) - and less than 0.1% Carbon Dioxide (CO₂).

Carbonitriding

Carbonitriding is a variation of carburising where both carbon and nitrogen bearing gasses are used, This is most usually by the inclusion of ammonia in with the carburising gas mixture. Carbonitriding is carried out in the austenite state, i.e. temperatures above 850°C, typically 870°C. The case depths are typically lower than those achieved by carburising alone however the surface hardness levels can be higher.

Low Pressure Carburising (Vacuum Carburising)

A reasonably modern process used to carburise components in an oxidising free environment.

The process is carried out at high temperature in a vacuum furnace utilising pulsed hydrocarbon gasses such as propane, ethylene and acetylene as the carburising medium.

The principle benefits are, an oxide free surface, low distortion, good finish, good penetration for complex shapes and holes, with consistent process performance and improved processing times

The process is not suitable for all steels and is used mainly for injection and transmission parts in the aerospace and automotive industries. Due to the relatively low quench pressure the treatment is not used universally across all steel and alloy types.

Gas Nitriding

Gas Nitriding involves the diffusion of nitrogen into the surface layers of a low carbon steel which is being held at an elevated temperature. This forms a nitrided layer, which improves surface hardness. Nitriding is typically carried out in the temperature range of 500 - 575°C where the material is in the ferritic state rather than the austenitic region used for carburising. This is possible since ferrite has a much higher solubility for nitrogen than it does for carbon.

The use of lower processing temperatures and the absence of the need to provide quenching leads to lower work piece distortion rates.

The advantage of nitriding in the ferritic state is that any previous heat treatment of the steel component is not disrupted and there is little / no distortion of the final component shape. This means that higher carbon steels that have been previously heat treated, can be surface hardened by nitriding. In fact it is normal to complete all thermal treatments to the component prior to Nitriding.

Ammonia NH₃ is the most common gas used for nitriding in batch furnaces.

One disadvantage is that some process cycles can be lengthy, up to 80 hours is not uncommon.

Nitrocarburising

Ferritic Nitrocarburising conducted at 550-580 °C or Austenitic Nitrocarburising conducted at 590 - 720 °C involves enrichment of the surface with both nitrogen and carbon to impart a compound layer consisting of iron-carbonitride. The Compound layer is apparent on the surface of the nitrogen bearing diffusion zone and greatly changes surface characteristics. The process may include subsequent quenching of the parts or other post process activities to further enhance the surface Compound layer.

Plasma Diffusion

Plasma diffusion treatment aims at introducing species like nitrogen, carbon,† boron, e.t.c into the surface of a component by bringing an activated gas into direct contact with the surface, which is being maintained at an elevated temperature. The plasma of an electrical glow discharge is used to derive positive ions from the active gas to produce the Nitriding, Carburizing or Boriding process. This adds greatly to surface treatment to improve surface hardness and to create wear fatigue and corrosion resistant properties.

Plasma Nitriding

Is particularly popular with common batch styles. In this process nitrogen atoms are diffused of into the metal surface in presence of a plasma environment.

This process is also called Ion nitriding where a differential potential of minimum voltage is applied to two electrodes held in a gas at reduced pressure, the work piece is maintained within the abnormal glow discharge region and as an increasing voltage and current are

applied to the electrodes, the work piece becomes heated through the action of ionic bombardment.

As a result nitrogen is transferred to the work piece, which then penetrates the surface by diffusion.

Other specialist processes

Surface Diffusion

Salt Baths

A method of providing thermal processing of steels using a bath of molten salts. The process prevents oxidation and provides a very uniform heating environment for hardening, tempering or quenching. The type of salt used depends on the temperature range required. For hardening, sodium cyanide, sodium carbonate and sodium chloride are in common use.

The process is also used for specialist Nitriding processes.

Due to environmental issues the process is becoming less popular in favour of other heat treatment methods Aluminising

As the operating temperature for gas turbines has increased beyond the natural safe operating point for the core alloys a process has been evolved to diffuse alumina on to the surface of the blades to form a protective oxide alumina layer. Most blades coatings have been applied by pack cementation where the blades are laid into trays of powder and subject to thermal process under atmosphere controlled conditions.

Because of the complexity of blade structure and associated cooling holes it is becoming more appropriate to carry out this process by chemical vapour deposition.

Hot Iso Static Processing (HIPping)

This process is used for the densification of castings and pre-sintered components as well as in the diffusion bonding of alloys. The process usually uses very high temperatures and pressures within a specially designed vessel.

Sintering

Treatments, which strengthen the molecular bonding of powder compacted components.

Many products with complex cross sectional forms are manufactured from powdered, core material, which is pressed or moulded into the component shape.

Sintering takes place in an atmosphere controlled environment and is used to strengthen the bonding of powder compacted components over a timed temperature process cycle.

EUROTHERM LIMITED UK

Faraday Close Durrington Worthing BN13 3PL
Tel. +44 (0)1903 268500 Fax +44 (0)1903 695666
Email info@eurotherm.co.uk
www.eurotherm.co.uk

EUROTHERM US

741-F Miller Drive Leesburg VA 20175-8993
Tel. 1-703-443-0000 Fax 1-703-669-1300
Email info@eurotherm.com
www.eurotherm.com

EUROTHERM WORLDWIDE

www.eurotherm.co.uk/contact.asp

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