Chapter 5: Structure and Strengthening of Metal Alloys by Heat Treatment

Introduction. The properties and behavior of metals and alloys during manufacturing into a product and their performance during their **service life** depend on their composition, structure, and their processing history and the **heat treatment** to which they have been subjected. Important properties such as strength, hardness, ductility, **toughness**, and resistance to **wear** are greatly influenced by **alloying** elements and the heat-treatment processes employed. The properties of **non-heat-treatable alloys** are improved by mechanical working, such as rolling, forging, and **extrusion**.

Structure of Alloys. In **pure metals**, the atoms are all of the same type, except for the presence of rare impurity atoms. Commercially pure metals are used for various purposes, such as aluminum for foil and copper for electrical conductors. Pure metals have somewhat limited properties but they can be enhanced and modified by **alloying.** An alloy consists of two or more chemical elements, at least one of which is a metal; the majority of metals used in engineering applications are some form of alloy. Alloying consists of two basic forms: **solid solutions** and **intermetallic compounds**.

Phase Diagrams A phase (**equilibrium**) diagram, shows the relationships among temperature, composition, and the phases present in a particular alloy system at equilibrium. Equilibrium means that the state of a system does not vary with time. Three types of phase diagrams include those for (a) complete solid solutions; (b) **eutectics**, such as **cast irons**; and (c) **eutectoids**, such as **steels**.

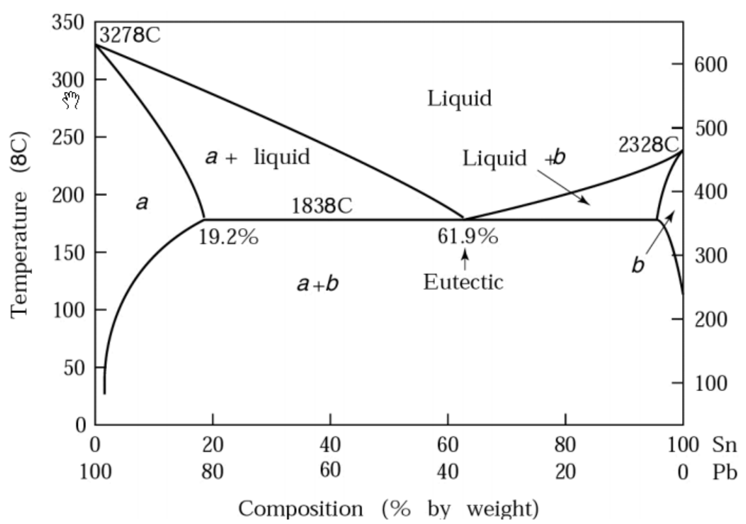

Fig. 1 The lead-**tin** phase diagram. Note that the composition of the eutectic point for this alloy is 61.9% Sn-38.1% Pb.
A composition either lower or higher than this ratio will have a higher **liquidus** temperature.

A. Fill in the blanks with the following words.

carbide, cast, structure, binary, austenite

The Iron–Carbon System Steels and cast irons are represented by the iron–carbon **……………… system**. Commercially pure iron contains up to 0.008% C, steels up to 2.11% C, and cast irons up to 6.67% C, although most …………….. irons contain less than 4.5% C. The iron–iron-carbide phase diagram is shown in Fig. 2.

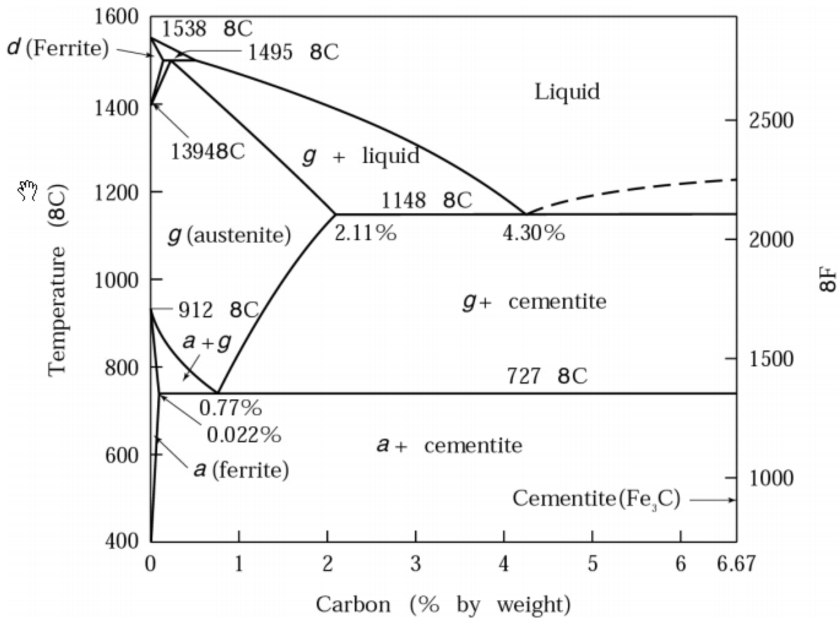

Fig. 2 The iron-carbide phase diagram.

Alpha ferrite, also denoted α -ferrite or simply ferrite, is a solid solution of body-centered cubic (bcc) iron; it has a maximum solid solubility of 0.022% C at a temperature of 727°C. As shown in Fig. 2, within a certain temperature range iron undergoes a **polymorphic transformation** from a BCC to an FCC structure, becoming gamma iron (γ -iron), or, more commonly, **…………………** (after the British metallurgist W.C. Roberts Austen, 1843– 1902). This …………….. has a solid solubility of up to 2.11% C at 1148°C. The right boundary of Fig. 2 represents **cementite**, which is 100% iron carbide (Fe_3C), having a carbon content of 6.67%. Cementite (from the Latin *caementum,* meaning "stone chips") is also called **…………………..**, but should not be confused with other carbides used as dies, cutting tools, and abrasives, such as tungsten carbide, titanium carbide, and silicon carbide.

Heat Treatment. The microstructure of heat-treatable alloys can be modified by heat-treatment techniques—that is, by controlled heating and cooling of the alloys at various rates. These treatments induce **phase transformations**, which greatly influence such mechanical properties as strength, hardness, ductility, toughness, and wear resistance. The effects of thermal treatment depend on the particular alloy, its composition and microstructure, the degree of prior cold work, and the rates of heating and cooling during heat treatment.

The percentage of austenite transformed into pearlite (for iron–carbon alloy) is a function of temperature and time. This transformation is best illustrated by **isothermal transformation** (IT) diagrams, or **time–temperature–transformation** (TTT) diagrams (see Fig. 3). The higher the temperature or the longer the time, the more austenite is transformed into pearlite.

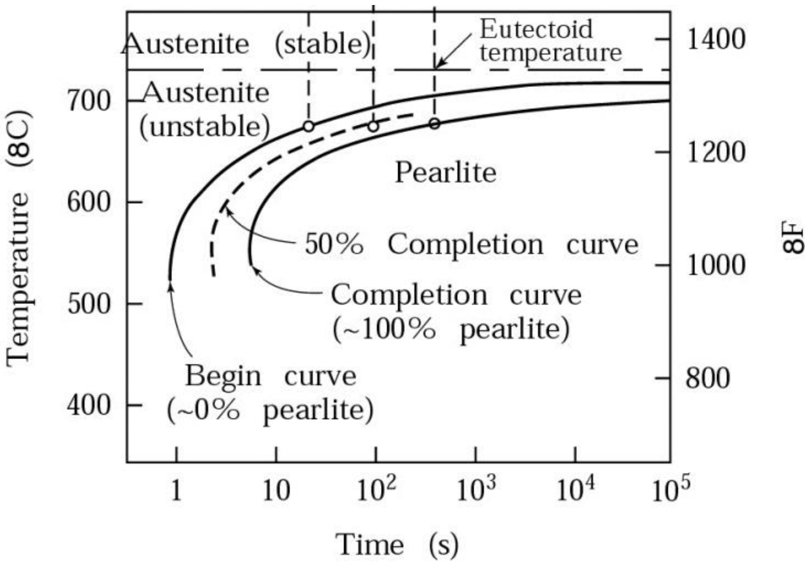

Fig. 3 Isothermal transformation diagram of iron-carbon alloy for the transformation temperature of 675°C.

Hardenability The capability of an alloy to be hardened by heat treatment is called its hardenability, and is a measure of the depth of hardness that can be obtained by heating and subsequent **quenching**. The term "hardenability" should not be confused with "hardness," which is the resistance of a material to indentation or scratching

Heat Treatment of Nonferrous Alloys and Stainless Steels Nonferrous alloys and some stainless steels cannot be heat treated by the heat-treatment techniques of ferrous alloys. The reason is that nonferrous alloys do not undergo phase transformations like those in steels; the hardening and strengthening mechanisms for these alloys are fundamentally different. Heat-treatable aluminum alloys, copper alloys, and **martensitic** and some other stainless steels are hardened and strengthened by a process called **precipitation hardening.** In this process, small particles of a different phase, called **precipitates,** are uniformly dispersed in the matrix of the original phase. Precipitates form because the solid solubility of one element (one component of the alloy) in the other is exceeded.

B. Fill in the blanks with the following words.

failure, toughness, surface, indentation

Case Hardening It is not always desirable to **through harden** parts, because a hard part lacks the required …………….. for some applications. For example, a small surface crack could propagate rapidly through a part and cause sudden and total ……………. . In many cases, modification of only the surface properties of a part (hence, the term **……………… or case hardening**) is desirable. This widely used method is particularly useful for improving resistance to surface …………………, fatigue, and wear. Typical applications for case hardening are gear teeth, cams, shafts, bearings, fasteners, pins, automotive clutch plates, tools, and dies. Several case-hardening processes are available; such as Carburizing, Carbonitriding, Flame hardening, Induction hardening and Laser-beam hardening.

C. Fill in the blanks with the following words.

residual, thermal, ductility, inert, furnace

Annealing Annealing is a general term used to describe the restoration of a cold-worked or heat treated alloy to its original properties— for instance, to increase …………….. (and hence **formability**) and to reduce hardness and strength, or to modify the microstructure of the alloy. The annealing process is also used to **relieve ……………… stresses** in a part, as well as to improve **machinability** and **dimensional stability**. The term "annealing" also applies to the ………………….. treatment of glass and similar products, castings, and **weldments**. The annealing process consists of the following steps: 1. Heating the workpiece to a specific temperature in a **……………………**, 2. Holding it at that temperature for a period of time (**soaking**), 3. Cooling the workpiece, in air or in a furnace. The annealing process may be carried out in an **…………………** or a controlled atmosphere, or it may be performed at lower temperatures to minimize or prevent surface oxidation.

Stress-relief Annealing. To reduce or eliminate residual stresses, a workpiece is generally subjected to stress-relief annealing, or **stress relieving**.

Tempering. If steels are hardened by heat treatment, tempering (also called **drawing**) is used in order to reduce **brittleness**, increase ductility and toughness, and reduce residual stresses.

Austempering. In austempering, the heated steel is quenched from the austenitizing temperature rapidly, to avoid formation of ferrite or **pearlite**. It is held at a certain temperature until isothermal transformation from austenite to bainite is complete. It is then cooled to room temperature, usually in still air and at a moderate rate in order to avoid thermal gradients within the part. The quenching medium most commonly used is molten salt, at temperatures ranging from 160°C to 750°C.

Heat-treating Furnaces and Equipment. Two basic types of furnaces are used for heat treating: **batch furnaces** and **continuous furnaces**. Because they consume much energy, their **insulation** and efficiency are important design considerations, as are their initial cost, the personnel needed for their operation and **maintenance**, and their safe use. In a batch furnace, the parts to be heat treated are loaded into and unloaded from the furnace in individual batches. The furnace basically consists of an insulated chamber, a heating system, and an access door or doors. Basic types of batch furnaces are box, **pit**, **bell** and elevator furnaces. In a continuous furnace, the parts to be heat treated move continuously through the furnace on **conveyors** of various designs.

Case Study: Heat treatment of automotive components?

The automotive industry is an important global economic driver. Requirements and stresses on components from this sector are increasing daily. Topics such as driving comfort, service life or the environment are now more important than ever. In order to meet these high demands, it is important that metallic components which are installed in large numbers in the automotive industry (engine blocks, shafts, cylinder heads, gears, etc.) are subjected to specific and correct heat treatment. For example, in the case of crankshaft, a surface treatment may be necessary to increase the material strength in the surface layer and to improve the wear behavior. Suitable thermo-chemical processes are gas nitriding, nitrocarburising, plasma nitriding and case hardening. The addition of nitrogen results in an increase in strength and a build-up of compressive stresses, which leads to improved load-bearing capacity of the crankshaft. And in the case of valves, heat treatment is used to achieve high wear and corrosion resistance, high temperature resistance and scale resistance and thus significantly extend the service life of these parts.

Fig. 4 A typical automotive crankshaft.

Video: What is induction heating? (Click this link).

E. Translate the following sentences into English.

۱. نمودارهای فازی، فازهای مختلفی که به عنوان تابعی از ترکیب آلیاژی و دما تشکیل می‌شوند را به صورت گرافیکی نمایش می‌دهند.

۲. مکانیزم های سخت کردن و استحکام دهی آلیاژهای فلزی اساساً شامل گرم کردن آلیاژ و متعاقباً کوئینچ کردن آن با سرعت های خنک کاری متفاوت است.

۳. کربن زدایی پدیده ای است که در آن آلیاژها در نتیجه عملیات حرارتی یا کار داغ در یک محیط (معمولاً اکسیژن که با کربن واکنش می دهد) از سطوح خود کربن از دست می دهند.