Module 4
Design for Assembly
Lecture 7

Design for Heat Treatment
**Instructional objectives**

By the end of this lecture, the student will learn

1. different heat treatment processes,
2. application of various heat treatment processes, and
3. design recommendation to get the good quality heat treated component.

**Introduction**

The heat treatment includes heating and cooling operations or the sequence of two or more such operations applied to any material in order to modify its metallurgical structure and alter its physical, mechanical and chemical properties. Usually it consists of heating the material to some specific temperature, holding at this temperature for a definite period and cooling to room temperature or below with a definite rate. *Annealing, Normalizing, Hardening* and *Tempering* are the four widely used heat treatment processes that affect the structure and properties, and are assigned to meet the specific requirements from the semi-fabricated and finished components. Steels being the most widely used materials in major engineering fabrications undergo various heat treatment cycles depending on the requirements. Also aluminum and nickel alloys are exposed to heat treatment for enhancement of properties. A brief discussion on the principles of various heat treatment processes of steels are presented in the text to follow.

**Annealing**

Annealing refers to a wide group of heat treatment processes and is performed primarily for homogenization, recrystallization or relief of residual stress in typical cold worked or welded components. Depending upon the temperature conditions under which it is performed, annealing eliminates chemical or physical non-homogeneity produced of phase transformations. Few important variants of annealing are full annealing, isothermal annealing, spheroidise annealing, recrystallization annealing, and stress relief annealing.

**Full annealing (conventional annealing)**

Full annealing process consists of three steps. First step is heating the steel component to above $A_3$ (upper critical temperature for ferrite) temperature for hypoeutectoid steels and above $A_1$ (lower critical temperature) temperature for hypereutectoid steels by 30-50°C (*Figures 4.7.1* and *4.7.2*). In *Figure 4.7.2*, the terms $\alpha$, $\gamma$ and Fe$_3$C refer to ferrite, austenite and cementite phases.
The second step is holding the steel component at this temperature for a definite holding (soaking) period of at least 20 minutes per cm of the thick section to assure equalization of temperature throughout the cross-section of the component and complete austenitization. Final step is to cool the hot steel component to room temperature slowly in the furnace, which is also called as **furnace cooling**. The **full annealing** is used to relieve the internal stresses induced due to cold working, welding, etc, to reduce hardness and increase ductility, to refine the grain structure, to make the material homogenous in respect of chemical composition, to increase uniformity of phase distribution, and to increase machinability.

![Iron-carbon phase equilibrium diagram](image1)

**Figure 4.7.1** Iron-carbon phase equilibrium diagram [1]

![Schematic representation of annealing operation](image2)

**Figure 4.7.2** Schematic representation of annealing operation [2]
Isothermal annealing

Isothermal annealing consists of four steps. The first step is heating the steel components similar as in the case of full annealing. The second step is slightly fast cooling from the usual austenitizing temperature to a constant temperature just below A<sub>1</sub>. The third step is to hold at this reduced temperature for sufficient soaking period for the completion of transformation and the final step involves cooling the steel component to room temperature in air. Figure 4.7.3 depicts the heat treatment cycles of full annealing and isothermal annealing. The terms α, γ, P, P<sub>S</sub> and P<sub>F</sub> refer to ferrite, austenite, pearlite, pearlite starting and pearlite finish, respectively.

Isothermal annealing has distinct advantages over full annealing which are given below.

1. Reduced annealing time, especially for alloy steels which need very slow cooling to obtain the required reduction in hardness by the full annealing.
2. More homogeneity in structure is obtained as the transformation occurs at the same time throughout the cross section.
3. Improved machinability and surface finish is obtained after machining as compared to that of the full annealed components.

Isothermal annealing is primarily used for medium carbon, high carbon and some of the alloy steels to improve their machinability.

Figure 4.7.3  Heat treatment cycles of full annealing and isothermal annealing [7].
Spheroidise annealing

Spheroidise annealing is one of the variant of the annealing process that produces typical microstructure consisting of the globules (spheroid) of cementite or carbides in the matrix of ferrite. The following methods are used for spheroidise annealing

Holding at just below $A_1$

Holding the steel component at just below the lower critical temperature ($A_1$) transforms the pearlite to globular cementite particles. But this process is very slow and requires more time for obtaining spheroidised structure.

Thermal cycling around $A_1$

In this method, the thermal cycling in the narrow temperature range around $A_1$ transforms cementite lamellae from pearlite to spheroidal. Figure 4.7.4 depicts a typical heat treatment cycle to produce spheroidised structure. During heating above $A_1$, cementite or carbides try to dissolve and during cooling they try to re-form. This repeated action spheroidises the carbide particles. Spheroidised structures are softer than the fully annealed structures and have excellent machinability. This heat treatment is utilized to high carbon and air hardened alloy steels to soften them and to increase machinability, and to reduce the decarburization while hardening of thin sections such as safety razor blades and needles.

![Figure 4.7.4](image)

Figure 4.7.4  A typical heat treatment cycle to produce spheroidised structure [7].
Recrystallization annealing

Recrystallization annealing process consists of heating a steel component below $A_1$ temperature i.e. at temperature between $625^0C$ and $675^0C$ (recrystallization temperature range of steel), holding at this temperature and subsequent cooling. This type of annealing is applied either before cold working or as an intermediate operation to remove strain hardening between multi-step cold working operations. In certain case, recrystallization annealing may also be applied as final heat treatment. The cold worked ferrite recrystallizes and cementite tries to spheroidise during this annealing process. Recrystallization annealing relieves the internal stresses in the cold worked steels and weldments, and improves the ductility and softness of the steel. Refinement in grain size is also possible by the control of degree of cold work prior to annealing or by control of annealing temperature and time.

Stress relief annealing

Stress relief annealing process consists of three steps. The first step is heating the cold worked steel to a temperature between $500^0C$ and $550^0C$ i.e. below its recrystallization temperature. The second step involves holding the steel component at this temperature for 1-2 hours. The final step is to cool the steel component to room temperature in air.

The stress relief annealing partly relieves the internal stress in cold worked steels without loss of strength and hardness i.e. without change in the microstructure. It reduces the risk of distortion while machining, and increases corrosion resistance. Since only low carbon steels can be cold worked, the process is applicable to hypoeutectoid steels containing less than 0.4% carbon. This annealing process is also used on components to relieve internal stresses developed from rapid cooling and phase changes.

Normalizing

Normalizing process consists of three steps. The first step involves heating the steel component above the $A_3$ temperature for hypoeutectoid steels and above $A_{cm}$ (upper critical temperature for cementite) temperature for hypereutectoid steels by $30^0C$ to $50^0C$ (Figure 4.7.5). The second step involves holding the steel component long enough at this temperature for homogeneous austenization. The final step involves cooling the hot steel component to room temperature in still air. Due to air cooling, normalized components show slightly different structure and properties than annealed components. The same are explained in Table 4.7.1.
The properties of normalized components are not much different from those of annealed components. However, normalizing takes less time and is more convenient and economical than annealing and hence is a more common heat treatment in industries. Normalizing is used for high-carbon (hypereutectoid) steels to eliminate the cementite network that may develop upon slow cooling in the temperature range from point $A_{cm}$ to point $A_1$. Normalizing is also used to relieve internal stresses induced by heat treating, welding, casting, forging, forming, or machining. Normalizing also improves the ductility without reducing the hardness and strength.

**Table 4.7.1** The variation in the properties of the annealed and normalized components [7]

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<th>Annealed</th>
<th>Normalised</th>
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<td></td>
<td>Less hardness, tensile strength and toughness.</td>
<td>Slightly more hardness, tensile strength and toughness.</td>
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<td></td>
<td>Pearlite is coarse and usually gets resolved by the optical microscope.</td>
<td>Pearlite is fine and usually appears unresolved with optical microscope.</td>
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<td></td>
<td>Grain size distribution is more uniform.</td>
<td>Grain size distribution is slightly less uniform.</td>
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<td></td>
<td>Internal stresses are least.</td>
<td>Internal stresses are slightly more.</td>
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**Figure 4.7.5** Normalizing [3]

**Hardening**

Different techniques to improve the hardness of the steels are conventional hardening, martempering and austempering.
Conventional hardening

Conventional hardening process consists of four steps. The first step involves heating the steel to above A$_3$ temperature for hypoeutectoid steels and above A$_1$ temperature for hypereutectoid steels by 50$^\circ$C. The second step involves holding the steel components for sufficient soaking time for homogeneous austenization. The third step involves cooling of hot steel components at a rate just exceeding the critical cooling rate of the steel to room temperature or below room temperature. The final step involves the tempering of the martensite to achieve the desired hardness. Detailed explanation about tempering is given in the subsequent sections. In this conventional hardening process, the austenite transforms to martensite. This martensite structure improves the hardness.

Following are a few salient features in conventional hardening of steel.

1. Proper quenching medium should be used such that the component gets cooled at a rate just exceeding the critical cooling rate of that steel.
2. Alloy steels have less critical cooling rate and hence some of the alloy steels can be hardened by simple air cooling.
3. High carbon steels have slightly more critical cooling rate and has to be hardened by oil quenching.
4. Medium carbon steels have still higher critical cooling rates and hence water or brine quenching is necessary.

Figure 4.7.6 depicts the conventional hardening process which involves quenching and tempering. During quenching outer surface is cooled quicker than the center. Thinner parts are cooled faster than the parts with greater cross-sectional areas. In other words the transformation of the austenite is proceeding at different rates. Hence there is a limit to the overall size of the part in this hardening process.

Martempering (marquenching)

Martempering process overcomes the limitation of the conventional hardening process. Figure 4.7.7 depicts the martempering process. This process follows interrupted quenching operation. In other words, the cooling is stopped at a point above the martensite transformation region to allow sufficient time for the center to cool to the temperature as the surface. Further cooling is continued through the martensite region, followed by the usual tempering. In this process, the
transformation of austenite to martensite takes place at the same time throughout the structure of the metal part.

![Figure 4.7.6](image1.png)  
**Figure 4.7.6** Heat treatment cycle for conventional hardening process [4].

![Figure 4.7.7](image2.png)  
**Figure 4.7.7** Heat treatment cycle for martempering [4]

**Austempering**

This process is also used to overcome the limitation of the conventional hardening process.  
**Figure 4.7.8** depicts the austempering process. Here the quench is interrupted at a higher temperature than for martempering to allow the metal at the center of the part to reach the same temperature as the surface. By maintaining that temperature, both the center and surface are allowed to transform to bainite and are then cooled to room temperature. Austempering causes
less distortion and cracking than that in the case of martempering and avoids the tempering operation. Austempering also improves the impact toughness and the ductility of the metal than that in the case of martempering and conventional hardening.

![Heat treatment cycle for austempering](image)

**Figure 4.7.8** Heat treatment cycle for austempering [4].

Tempering
The hardened steel is not readily suitable for engineering applications. It possesses following three drawbacks.

- Martensite obtained after hardening is extremely brittle and will result in failure of engineering components by cracking.
- Formation of martensite from austenite by quenching produces high internal stresses in the hardened steel.
- Structures obtained after hardening consists of martensite and retained austenite. Both these phases are metastable and will change to stable phases with time which subsequently results in change in dimensions and properties of the steel in service.

Tempering helps in reduce these problems. Tempering is achieved by heating hardened steel to a temperature below A₁, which is in the range of 100°C to 680°C, hold the component at this temperature for a soaking period of 1 to 2 hours (can be increases up to 4 hours for large sections and alloy steels), and subsequently cooling back to room temperature.

The tempering temperature is decided based on the type of steel. Highly alloyed tool steels are tempered in the range of 500°C - 600°C. Low alloy construction steels are tempered above 400°C.
to get a good combination of strength and ductility. Spring steels are tempered between $300^0\text{C} - 400^0\text{C}$ to get the desired properties. *Figure 4.7.9* depicts the influence of tempering temperature on the properties of steel. It is observed that the increase in the tempering temperature decreases the hardness and internal stresses while increases the toughness.

![Variation in properties with tempering temperature](image)

**Figure 4.7.9** Variation in properties with tempering temperature [7].

**Defects in Heat Treatment**

Heat treatment of steels or aluminum can lead to several defects. The principal types of defects found in quenching of steels are internal and external cracks in the work, distortion and warping.

**Crack**

When the internal tensile stresses exceed the resistance of the steel to separation the crack occurs. The insertion of the tools in the furnace without preheating for tempering is one of the main causes of crack propagation. The crack formation is reduced by preheating the tool between $200^0\text{C}$ to $300^0\text{C}$.

**Distortion**

Distortion occurs due to uneven heating, too fast cooling, part incorrectly supported in furnace, incorrect dipping in quenching and stresses present before preheating. Distortion can be
Prevented by preheating the tool or check furnace capacity, reduce the hardening temperature, and by reviewing the method of dipping.

Warping

Asymmetrical distortion of the work is often called warping in heat-treating practice. Warping is usually observed upon non-uniform heating or over heating for hardening. It also occurs when the work is quenched in the wrong position and when the cooling rate is too high in the temperature range of the martensite transformation. An elimination of these causes should subsequently reduce warping.

Typical Design Guidelines in Heat Treatment

1. The properties required in the heat treated part are obtained without the parts being distorted beyond the acceptable limits.
2. The ideal design for a heat treatable part is the shape that when heated (or cooled) would have the same temperature at every point with in the part.
3. Abrupt change in the section sizes must be avoided. Figure 4.7.10(a) depicts the recommended design.
4. Long thin parts like connecting rods are recommended to have symmetrical and rounded cross sections to reduce stresses [Figure 4.7.10(b)].
5. The holes in a part are centered so that the mass of metal surrounding them is equally balanced [Figure 4.7.10(c)].
6. All internal corners in a part should be rounded, and non-cutting holes should have radii at the top or bottom surfaces [Figures 4.7.10(d) and (e)].
7. The irregular shaped or the unbalanced die sections are recommended for two piece construction [Figure 4.7.10(f)].
8. The rounded corners at the base of the gear and ratchet teeth and at the bottom of keyways reduce heat treatment stress concentrations [Figure 4.7.10(g)].
9. A sectional sprocket or gear design avoids stresses due to unbalanced sections [Figure 4.7.10(h)].
10. Through holes provide more uniform section thickness and reduce heat treating problems [Figure 4.7.10(i)].
**Figure 4.7.10** Design recommendations for heat treated components [8].

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Figure 4.7.10 Design recommendations for heat treated components [8] [continued]

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Exercise

1. Why hardening is always followed by tempering?
2. Hardening process leads to the formation of Martensite. Which characteristic of Martensite is responsible for the increased hardness?

References

6. Y. Lakhtin and N. Weinstein, “Engineering physical metallurgy and heat treatment”,