

Steel microstructure after thermal and chemo-thermal reprocessing of steel

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ABSTRACT

Various researchers have long studied heat treatment of steel. In the process of mechanical engineering, machine parts are formed by heat. The article deals with a brief summary of the thermal and chemo-thermal reprocessing of steel. The range of heating temperatures during annealing and quenching is determined. The structure of steel and its properties are considered. The research characteristic of all stages of chemo-thermal reprocessing of steel is carried out. Steel microstructure in the process of heat treatment of metal is studied.

Key words: steel microstructure, heat treatment, structure, metal.

1. INTRODUCTION

In mechanical engineering, machine parts are heat treated usually twice. The first pre-heat treatment is carried out for blanks to improve the technological properties, and after mechanical cutting, the final hardening heat treatment of machine parts is performed to ensure the mechanical, operational and other properties required by the working conditions in the machine.

Heat treatment is the process of processing materials by thermal action in order to change the structure and properties in a given direction.

Heat treatment is applied to work piece blanks, forgings, stampings, as well as finished parts and tools to give them the necessary properties: hardness, strength, wear resistance, elasticity, stress relieving, improving workability [1].

The essence of heat treatment is to heat the metal to a temperature that is slightly higher or lower than critical temperatures, expose it at these temperatures, and cool fast or slowly. During the cooling process, allotropic changes occur in the metal structure, resulting in dramatic changes in mechanical properties. Fast cooling increases hardness, wear resistance, elasticity, while slow cooling increases ductility, impact strength, and workability. In addition, there is a heat treatment associated with changes in the chemical composition of the product material, the so-called chemo-thermal reprocessing.

2. RESEARCH

The study was carried out during the heat treatment of engineering products in the course of which phase transformations of the first kind, taking place in the solid state at the stages of heating and cooling in iron-carbon alloys, are based on Figure 1.

The study shows that the temperatures at which phase and structural transformations occur in alloys of the Fe - Fe₃C system are called critical points and have symbols. All critical points are indicated by the letter A (from French arrest - stop). A1-pearlite (eutectoid) transformation (A_{C1} – during heating, Ar₁– during cooling) corresponds to line PSK of the iron – carbon diagram; A3-the beginning of ferrite precipitation from austenite during cooling (Ar₃), the end of ferrite dissolution during heating (A_{C3}), corresponds to line GS of the iron – carbon diagram; A4-transition of γ - iron to α - iron during heating (A_{C1}) and back when cooling (Ar₁); Acm – the beginning of cementite precipitation from austenite during cooling or the end of cementite dissolution during heating, corresponds to line E of the iron – carbon diagram [2,8].

In the process of slow heating in furnaces during quenching or annealing, when the temperature, designated t_{Ac1}, (for carbon steels 727⁰C) is reached, the phase transformation of pearlite into austenite occurs:

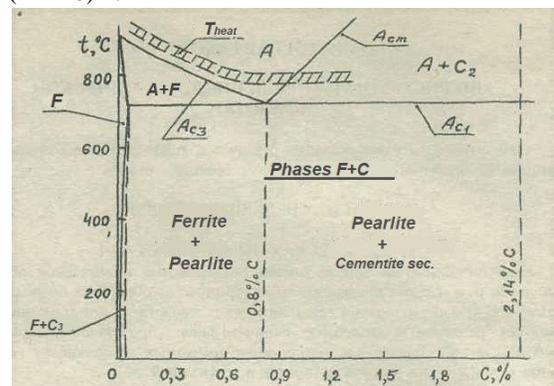
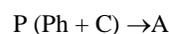


Figure 1: Heating temperature range during annealing and quenching

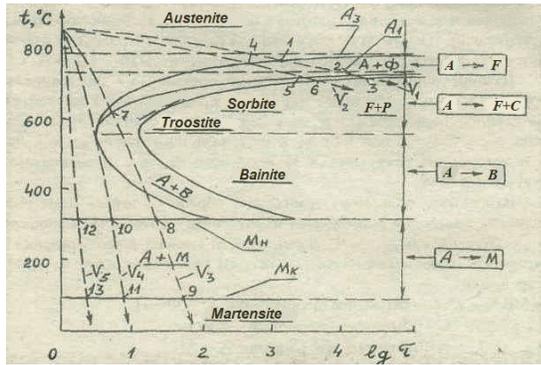


Figure 2: Diagram of isothermal transformation of under cooled austenite of hypoeutectoid steel

The austenite grains formed during the precipitation of ferrite and cementite in a large number of nuclei leads to the production of initial fine-grained austenite. In hypoeutectoid steels ($SP < S < S_s$), when heated in the temperature range $t_{Ac1} \dots t_{Ac3}$, the phase transformation of ferrite into austenite occurs after the conversion of $F \rightarrow A$. [3,7].

The cooling stage plays the most important role in heat treatment. This is the stage when the final microstructure of the part is formed from austenite. Depending on the degree of undercooling ($\Delta t = t_{A1} - t$) of austenite below the temperature t_{A1} (727°C), one of three phase transformations occurs:

1. $\approx 550^\circ\text{C} < t < t_{A1}$ -pearlite transformation: $A \rightarrow F + C$.
2. $t_{Mb} < t \leq 550^\circ\text{C}$ -bainitic transformation: $A \rightarrow B$.
3. $t_{Mc} < t \leq t_{Mb}$ -martensitic transformation: $A \rightarrow M$.

The designations t_{Me} and t_{Mb} refer to the temperatures of the beginning and end of the martensitic transformation. The temperature intervals of these phase transformations for one of the hypoeutectoid carbon steels are shown in the diagram of the isothermal transformation of undercooled austenite, which is constructed in temperature – time coordinates (logarithmic scale) (Fig. 3.2). In this diagram, horizontal dotted lines represent the temperatures of phase transformations A_{C1} and A_{C3} at equilibrium, and solid lines divide the diagram into areas with different phases (the diagram does not show the boundary between pearlite and bainitic transformations as a line) [4]. Cooling curves are also given: V1 – characterizes slow cooling (with a furnace – full annealing); V2 and V3 – faster cooling (V2 – still air cooling (normalizing annealing), V3 – in oil (partial quenching), V4-high cooling speed. V5-very high cooling speed (in water – full hardening).

3. RESULT AND DISCUSSION

Full and normalizing annealing are based on pearlite transformation, and quenching is based on martensitic transformation.

After quenching, another heat treatment is performed - tempering (heating to temperatures of $160\text{-}650^\circ\text{C}$, that is not higher than t_{A1} (727°C). Depending on the specific tempering temperature, different structures are formed.

Here is the steel structure example and its properties after heat treatment:

3.1 Ferrite (F)

Definition and structure: Solid solution of carbon in $\text{Fe}\alpha$. Limit solubility of carbon in $\text{Fe}\alpha$ at 727°C is about 0.02 %, at room temperature it is 0.06 %. Ferrite, like $\text{Fe}\alpha$, has a body-centered cubic lattice.

Properties: It is ferrimagnetic up to 786°C $\sigma_B = 25\text{kg/mm}^2$; $\sigma_T = 12\text{kg/mm}^2$; $\delta = 50\%$; $\psi = 80\%$; $\text{HB} 70\text{-}100$. Specific heat capacity of ferrite in $\text{kcal/kg}^\circ\text{C}$ is at:

- $100^\circ\text{C} - 0.1107$
- $200^\circ\text{C} - 0.1161$
- $300^\circ\text{C} - 0.1215$
- $400^\circ\text{C} - 0.1275$
- $500^\circ\text{C} - 0.1337$
- $600^\circ\text{C} - 0.1417$
- $700^\circ\text{C} - 0.1515$
- $800^\circ\text{C} - 0.1650$
- $900^\circ\text{C} - 0.1700$

Coefficient of thermal expansion of ferrite: $\alpha_{106} = 12.0\text{-}12.5 \text{ cm/cm}^\circ\text{C}$; thermal conductivity $\lambda = 66 \text{ kcal/phr}^\circ\text{C}$; molecular weight $M = 55.85$

3.2 Austenite (A)

Definition and structure: Solid solution of carbon in $\text{Fe}\gamma$. The maximum solubility of carbon in $\text{Fe}\gamma$ at 1130°C is 2 %, at 727°C is 0.8 %. Austenite, like $\text{Fe}\gamma$, has a face-centered cubic lattice [5].

Properties: In pure iron-carbon alloys, it is stable only at temperatures above 727°C . Austenite, like $\text{Fe}\gamma$, is not magnetic, it is viscous, and its hardness at a normal temperature is approximately $\text{HB} 180\text{-}22$. Austenite has a low thermal conductivity $\lambda = 36 \text{ kcal/phr}^\circ\text{C}$

The specific heat capacity of austenite at 100°C is $0.12 \text{ kcal/kg}^\circ\text{C}$, $\alpha_{106} = 17\text{-}24 \text{ cm/cm}^\circ\text{C}$ $M = 55.85$

3.3 Cementite (C)

Definition and structure: the chemical entity of iron with carbon (iron carbide) contains 6.67 % C. There are three varieties of cementite:

- 1) primary, disengaged during crystallization from a liquid alloy;
- 2) secondary, disengaged during cooling from austenite;
- 3) tertiary, disengaged during cooling from ferrite. It has a complex orthorhombic lattice with 12 iron atoms and 4 carbon atoms in its unit cell.

Properties: It is ferromagnetic up to 210°C , has a high hardness and brittleness; $\text{HB} 859\text{-}1100$ [6].

The specific heat capacity of cementite in $\text{kcal/kg}^\circ\text{C}$ is at:

- $100^\circ\text{C} - 0.1480$
- $200^\circ\text{C} - 0.1488$
- $300^\circ\text{C} - 0.1490$
- $400^\circ\text{C} - 0.1505$
- $500^\circ\text{C} - 0.1524$
- $600^\circ\text{C} - 0.1557$
- $700^\circ\text{C} - 0.1559$
- $800^\circ\text{C} - 0.1649$
- $900^\circ\text{C} - 0.1710$

$\alpha_{106} = 6.6\text{-}6.5 \text{ cm/cm}^\circ\text{C}$
 $\lambda = 6.1 \text{ kcal/phr}^\circ\text{C}$ $M = 179.5$

3.4 Pearlite (P)

Definition and structure: Eutectoid is a physical mixture of ferrite and cementite formed during the austenite decomposition. There are lamellar pearlite, which contains cementite plates in the ferritic matrix and granular pearlite,

which contains cementite grains in the ferritic matrix. There is 0.8% of pearlite in iron-carbon alloys.

Properties: Mechanical properties depend on the fineness degree (dispersion) of cementite particles. For example, thin-plate pearlite has $\sigma_B = 75 \div 80 \text{ kg/mm}^2$, $\delta = 8 \div 10 \%$.

Macrolaminar pearlite $\sigma_B = 60 \div 70 \text{ kg/mm}^2$, $\delta = 5 \div 7 \%$

Granular $\sigma_B = 55 \div 60 \text{ kg/mm}^2$; $\delta = 10 \div 14 \%$ The larger particles of cementite are, the lower its hardness is, which is within HB 160-250 $\alpha_{106} = 10,0 \div 11,0 \text{ cm/cm}^\circ\text{C}$ $\lambda = 44,6 \text{ kcal/phr}^\circ\text{C}$

3.5 Sorbite (S)

Definition and structure: the product of austenite decomposition within the temperature range of 600-650 °C is a physical mixture of ferrite and cementite, which differs from pearlite with a higher degree of dispersion and greater hardness. Sorbitol is also a product of martensite decomposition during its tempering (secondary sorbite)[6].

Properties: Quenching sorbite has an increased hardness (HRC 30). Secondary sorbite HRC 30-40. The hardness depends on the steel chemical composition, temperature, and tempering duration. Secondary sorbite has higher plasticity and viscosity.

3.6 Troostite (T)

Definition and structure: Dispersed mixture of supersaturated α -solid solution and cementite with a needle-like structure without differentiation of the structure's constituent particles. It is formed due to austenite decomposition in the zone of intermediate transformation. If the formation occurs in the upper area of the intermediate transformation, upper bainite is formed, and in the lower area, lower bainite is formed.

Properties: Properties depend on the carbon content. At 0.8 % C the upper bainite is HRC 40-50, the lower HRC 55 is characterized by high wear resistance and high mechanical properties.

3.7 Martensite (M)

Definition and structure: Supersaturated solid solution of carbon and other elements in Fe α , obtained as a result of diffusion-free transformation of austenite. The crystal lattice is volume-centered tetragonal.

Properties: It has a high hardness, which depends on the carbon content. It is ferromagnetic.

Annealing. For annealing with full phase recrystallization, the steel must be heated to the temperature of the austenitic state, exposed at this temperature until complete austenization and slowly cooled, thus, a diffusive phase transformation occurs with the formation of a ferrite-cementite mixture from austenite. A mixture of ferrite and cementite grows as colonies from separate centers at the boundaries of austenitic grains. The higher the cooling speed of steel is, the more austenite is undercooled below 727 °C.

Quench. The purpose of quenching is to obtain a high hardness of steel. This hardness is obtained if the steel is cooled at a speed greater than the critical quenching speed from the austenitic or austenitic-cementite state. As a result of rapid cooling, the diffusion-free transformation of austenite into martensite occurs, a supersaturated solid solution of carbon in α -iron with a tetragonal lattice. The solubility of carbon in α -iron at room temperature is negligible. In martensite, all the amount of carbon that was in the original austenite is preserved.

Hypereutectoid steel for quenching is heated higher than A_{C1} by 30-50 °C, exposed and quickly cooled in water, thus, it is not fully quenched. The structure of hypereutectoid steel after this heat treatment consists of martensitic and cementite. A hypereutectoid steel with this structure has a maximum hardness. After quenching, the steel is always tempered[7].

Tempering. During tempering, martensite-hardened steel is heated to a temperature lower than 727 °C. The main transformation during tempering of steel is martensite decomposition. Carbide precipitation from the supersaturated solution and the reduction of carbon concentration to the equilibrium concentration in ferrite occurs when the hardened steel is heated up to 400 °C. At temperatures above 400 °C, cementite particles are coagulated and spheroidized. The carbide is formed within the original martensitic needles. Therefore, the microstructure of the released steel retains a needle-like character and is similar to martensitic. This way two-phase ferrite-carbide mixture, obtained during the decomposition of martensite, differs from the ferrite-cementite mixture formed during the decomposition of undercooled austenite.

The microstructure of the surface layer consists of two zones: martensite and martensite + troostite, a transition layer of troostite and ferrite. In the core of the part, natural structure is preserved: ferrite and pearlite.

Chemical and heat treatment. During chemical-heat treatment, both thermal and chemical affect the material, which changes the chemical composition and structure in the surface layers of parts to a certain depth. To change the chemical composition of the surface layers, parts are placed in an active medium: gas, liquid, solid, from which a layer with a changed chemical composition and structure is formed as a result of atom adsorption of the saturable element by the surface of the part and further diffusion of the adsorbed atoms from the surface to a certain distance into the product [8].

The purpose of cementation is to create a high surface hardness with a viscous core. Therefore, low-carbon steel, usually containing up to 0.25% carbon, is cemented. When carburizing in a solid or gas environment at 900-950 °C, the carbon concentration in the surface layer usually reaches 0.9-1.0 %, while in the core, it does not exceed 0.25 %. After slow cooling of case hardening steel has a cross-section scheme of the structures of annealed steels of different composition. In the surface layer with a high concentration of carbon in it, the product has the structure of hypereutectoid steel with a thin cementite network, surrounding the pearlite colonies. The further from the surface, the thinner the cementite network is, the hypereutectoid steel gradually turns into eutectoid and hypoeutectoid steel. The further from the surface, in the zone of hypoeutectoid steel structure, the amount of excess ferrite continuously increases until the composition of the original steel is reached in the core.

Nitriding is usually used for medium-carbon alloy steels, pre-quenched and high-tempering to obtain a high-strength and high-viscosity sorbitol structure. After nitriding, dispersed nitrides of alloying elements are formed in the surface layer.

4. CONCLUSION

Thus, the industry uses cementation of the surface layer of steel with boron (borating), aluminum (aluminizing), silicon (siliconizing), chromium (chromizing) and other types of chemical and heat treatment. Thus, when saturated with boron (borating) followed by surface quenching, a layer of martensite structure is formed with a large zone of needle-like borides perpendicular to the surface. Diffusion boride coatings have high wear resistance. The wear resistance of borinated steel 45 under sliding friction conditions is 4-6 times higher than cemented ones and 2-3 times higher than nitro-cemented steels.

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