Heat Treatment of Steel

Steels can be heat treated to produce a great variety of microstructures and properties. Generally, heat treatment uses phase transformation during heating and cooling to change a microstructure in a solid state.

In heat treatment, the processing is most often entirely thermal and modifies only structure. Thermomechanical treatments, which modify component shape and structure, and thermochemical treatments which modify surface chemistry and structure, are also important processing approaches which fall into the domain of heat treatment.

The iron-carbon diagram is the base of heat treatment. Typical heat treatment operation is presented in Fig. 1.

Fig. 1. Thermal history of heat treatment operation.
According to cooling rate we can distinguish two main heat treatment operations:

- annealing – upon slow cooling rate (in air or with a furnace)
- quenching – upon fast cooling (in oil or in water)

Annealing - produces equilibrium structures according to the Fe-Fe₃C diagram
Quenching - gives non-equilibrium structures

Among annealing there are some important heat treatment processes like:

- normalising
- spheroidising
- stress relieving

**Normalising**
The soaking temperature is 30-50°C above A₃ or Aₑₘ in austenite field range. The temperature depends on carbon content. After soaking the alloy is cooled in still air. This cooling rate and applied temperature produces small grain size. The small grain structure improve both toughness and strength (especially yield strenght).

During normalising we use grain refinement which is associated with allotropic transformation upon heating $\gamma \rightarrow \alpha$ (Fig. 2).

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Fig. 2. Influence of temperature on an eutectoid steel grain size
Important: austenite does not change grain size during cooling!!

**Spheroidising**
The process is limited to steels in excess of 0.5% carbon and consists of heating the steel to temperature about $A_1$ (727°C). At this temperature any cold worked ferrite will recrystallise and the iron carbide present in pearlite will form as spheroids or “ball up”. As a result of change of carbides shape the strength and hardness are reduced.

**Quenching**
Soaking temperature 30-50°C above $A_3$ or $A_1$, then fast cooling (in water or oil) with cooling rate exceeding a critical value. The critical cooling rate is required to obtain non-equilibrium structure called martensite. During fast cooling austenite cannot transform to ferrite and pearlite by atomic diffusion.

Martensite is supersaturated solid solution of carbon in $\alpha$-iron (greatly supersaturated ferrite) with tetragonal body centered structure. Martensite is very hard and brittle. Martensite has a “needle-like” structure.

Kinetics of martensite transformation is presented by TTT diagrams (Time-Temperature-Transformation).
With the quenching-hardening process the speed of quenching can affect the amount of martensite formed. This severe cooling rate will be affected by the component size and quenching medium type (water, oil).
The critical cooling rate is the slowest speed of quenching that will ensure maximum hardness (full martensitic structure).
Tempering
This process is carried out on hardened steels to remove the internal stresses and brittleness created by the severe rate of cooling. The treatment requires heating the steel to a temperature range of between 200 and 600°C depending upon the final properties desired. This heat energy allows carbon atoms to diffuse out of the distorted lattice structure associated with martensite, and thus relieve some of the internal stresses. As a result the hardness is reduced and the ductility (which was negligible before tempering treatment) is increased slightly. The combined effect is to “toughen” the material which is now capable of resisting certain degree of shock loading. The higher the tempering temperature the greater the capacity for absorbing shock.
Rys. 5.3. Zmiany temperatury podczas procesu
Rys. 9.8. Zakresy temperatur wyżarzania stali na tle wykresu równowagi Fe-Fe₃C: 1 - ujędrnianie, 2 - przegrzewanie, 3 - normalizowanie, 4 - wyżarzanie zupełne, 5 - umarzanie (sferoidyzacja), 6 - rekrytalizowanie, 7 - odprężanie, 8 - stabilizowanie.
Rys. 9.7 Schemat zmian wielkości ziarna podczas nagrzewania i następującego po nim ochłodzenia w zakresie przemian perlit-austenit-perlit.
Rys. 9.9. Przebieg roczny temperatur w strefie oznaczającej ośrodek wód
Figure 5.23 Hardening range for carbon steels
RYS. 9.33. Sposoby hartowania objętościowego: a) zwykle, b) 1 – stopniowe, 2 – przyspieszone, c) hamulcowe 1 – izotermiczne, 2 – ciągłe, 3 – martempering
Rys. 5.29. Schematyczne wykresy przemian austenitu przekładania na ferrit, perlit, spęt zanieczyszczeń w CTP, przy chłodzeniu zanurzeniowym. $\gamma$ - austenit, $\alpha$ - ferrit, $P$ - perlit, $B$ - bainit, $M$ - martensyt.

Figure 5.24 Tempering temperature range for iron-carbon at 5.5.
Oil-quenched 4340

SINGLE HEAT RESULTS

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<tr>
<th>C</th>
<th>Mn</th>
<th>P</th>
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<th>Si</th>
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<th>Cr</th>
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Treatment: Normalized at 1600 F, reheated to 1475 F quenched in oil.

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Fig. 8.4. Change in mechanical properties with tempering temperature for oil-quenched 4340 steel. (Ref 8.3)