Department of Materials Science and Engineering

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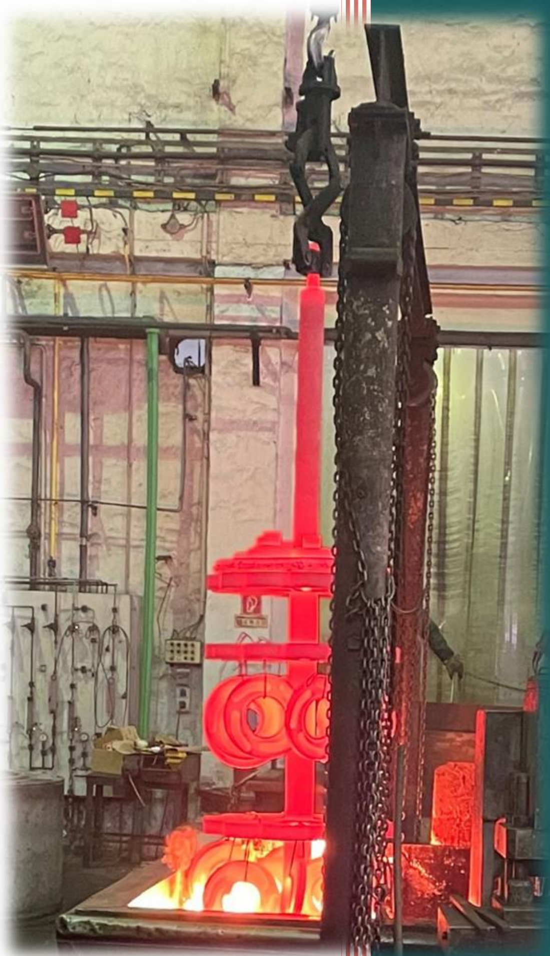
Effects of heat tretment



MŰEGYETEM 1782

Effects of heat treatment

Steel is essentially an Fe-C alloy that can be alloyed with additional elements to improve its properties. (The maximum carbon content of unalloyed steels is 2.1%, but in the case of some highly alloyed tool steels, this can be higher – Figure 1).

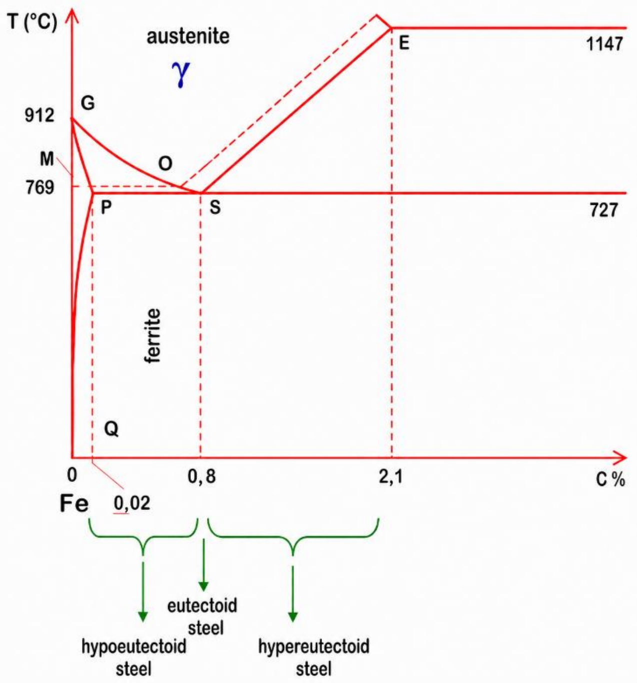


Figure 1. Fe-C phase diagram for steels

> Steel remains the most important group of engineering materials. Global steel production reached 1.7 billion tons last year, meaning that each person produces 200 kg of steel per year. This large-scale use is possible because:
>
> - it can be produced economically, its large-scale production is highly efficient, its recyclability is very advantageous,
>
> - its various properties (e.g. mechanical properties, corrosion behavior, etc.) can be influenced in a wide range by technological processes (forming, alloying, heat treatment and combinations thereof).
>
> Heat treatment can change the properties of steels over wide limits, so their toughness and strength can be adjusted to meet application requirements. The term heat treatment is a collective term for a series of procedures that can be used to change the structure of metals and their alloys according to our needs through thermal activation, without changing the shape or chemical composition of the treated object.

Heat treatment is a sequence of operations consisting of programmed heating, holding and cooling, which can be repeated several times with changed parameters. The purpose is to change the structure and stress state of the workpiece in order to achieve the required properties (strength, toughness, wear resistance, machinability, etc.).

All metallic materials can be heat treated, but steels (C<2.1%) are particularly suitable for influencing their properties by heat treatment. Steels are austenitized before the most common heat treatment operations we will discuss. The austenitic structure can be created under conditions by *isothermal* heating or *continuous* heating.

In practice, the cooling rate is not "infinitely slow", but faster. Depending on the cooling rate or the degree of supercooling, the transformation of austenite into a near-equilibrium state changes. Austenite transforms into pearlite between the A1 temperature and about 550 °C. With sufficiently fast cooling, in addition to the pearlite transformation, bainite and martensitic transformations can also occur. The faster the cooling (the less time available for the diffusion process), the closer the composition is to the austenite composition even after the allotropic transformation.

1. Austenizing diagrams

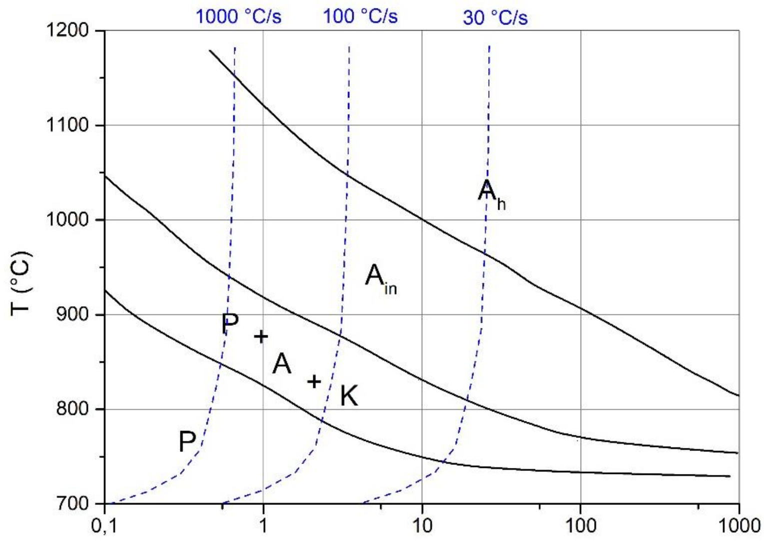
During heat treatment of steels, programmed heating is often carried out to the austenitic zone, where it is held and then cooled.

Austenite can be created in steels under real conditions by isothermal or continuous heating.

For austenitization under **isothermal conditions**, the heating must be so fast that the time required for austenitization is negligible, so that the austenitization process can be evaluated at a constant temperature – isothermally – i.e. the time required for the start and completion of austenite formation.

The usefulness of isothermal diagrams is limited, since in practice it is difficult or impossible to achieve isothermal heating conditions for larger components.

In the T-lg(t) diagram obtained during **continuous heating** (Figure 2), a heating-rate line is selected, indicating the onset of austenitization at A1 and its completion at A3. The transformation to austenite is complete at A3, but at this temperature the austenite is still inhomogeneous, i.e., it contains more carbon in the previously pearlitic areas and less carbon in the previously ferritic areas. The temperature and duration of austenitization must be chosen so that acceptable homogeneity, but still fine-grained austenite is formed for the heat treatment(s) starting from this state. The rate of continuous heating shifts the transformation towards higher temperatures and shorter times.



lg (t) (min)

Figure 2. Continuous austenitization diagram of eutectoid steel (C = 0.8 %)

2. Non-equilibrium transformation diagrams

The transformation process is influenced by two opposing effects: with ΔT overcooling, the transformation constraint increases (the critical seed size capable of transformation becomes smaller and smaller), but at the lower(er) temperature thus created, the diffusion rate decreases. These two effects together result in the time requirement of the austenite transformations, which depends on the 'T' temperature, being characterized by *C-shaped curves* in the T–lg(t) coordinate system. C-curves are important aids for the most commonly used heat treatment technologies.

Non-equilibrium transformations change not only the transformation temperatures, but also the quantitative and qualitative relationships of the microstructure elements formed during heating and cooling. Non-equilibrium transformations can be studied isothermally (at almost constant temperature) or during continuous cooling. Non-equilibrium transformation curves show the beginning and end of the austenite transformation and the microstructures formed from it.

The **isothermal transformation diagrams** for diffusion transformations **at constant temperature (isothermal)** show the time periods required for the transformations to begin and end (Figure 3), as well as the composition and hardness of the resulting microstructure. The isothermal transformation can only be carried out on small samples, by rapidly cooling the austenite (e.g. in a salt or metal bath) and then maintaining the temperature.

> In practice, isothermal transformation is used in the process of patenting, where the goal is usually to create a benitic tissue structure.

In reality, cooling is rarely isothermal, most often continuous, i.e. cooling from the heating temperature to room temperature occurs in a controlled manner. The desired change in microstructure determines the rate of cooling.

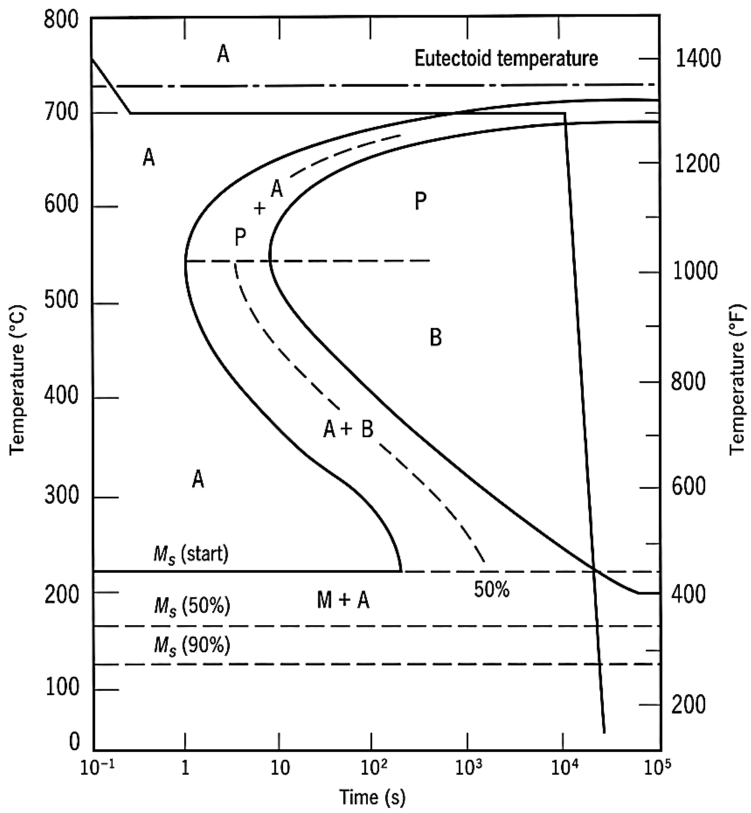


Figure 3. Isothermal diagram of eutectoidic steel

Continuous cooling transformation diagrams show the starting and ending temperatures of the transformations in the T-lg(t) coordinate system, along a cooling curve determined by a certain coolant. It is also showing durations and the expected microstructure elements or hardness values. The cooling rate can be fast (hardening, fixing effect), normal (usually in air) and slow (softening effect) (Figure 4).

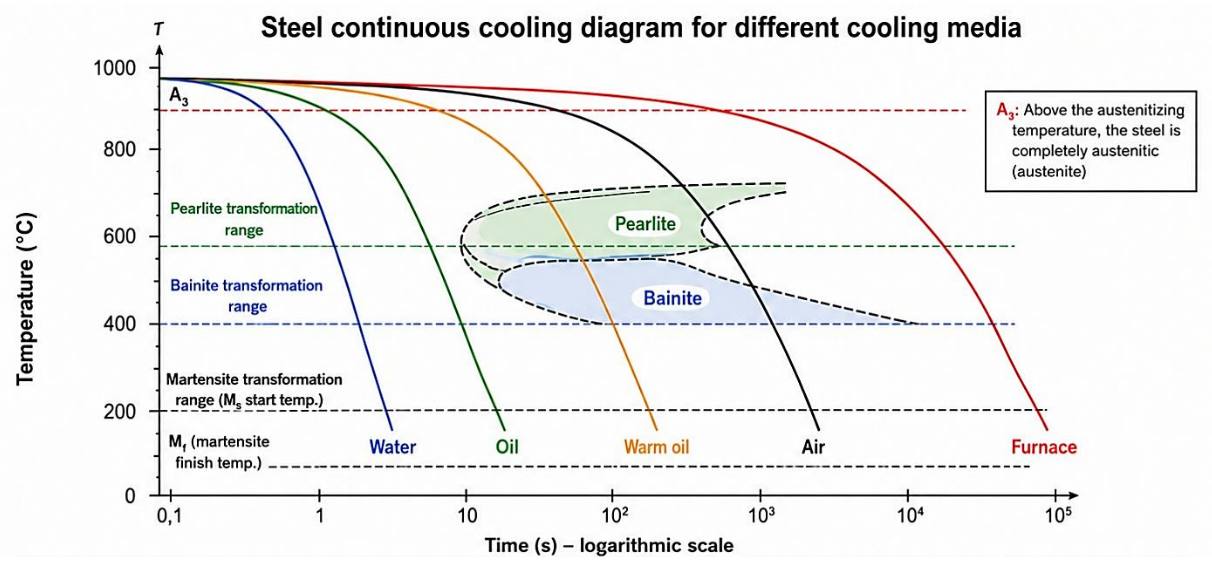


Figure 4. Effects of coolants during continuous cooling in the eutectoid case

In the continuous cooling curve, the beginning and end of the austenite transformation are indicated by the cooling curves. The percentage of transformed microstructures is presented along the lines indicating the end of each transformation, and the hardness of the resulting microstructure can be seen at the end of the cooling curves (Figure 5).

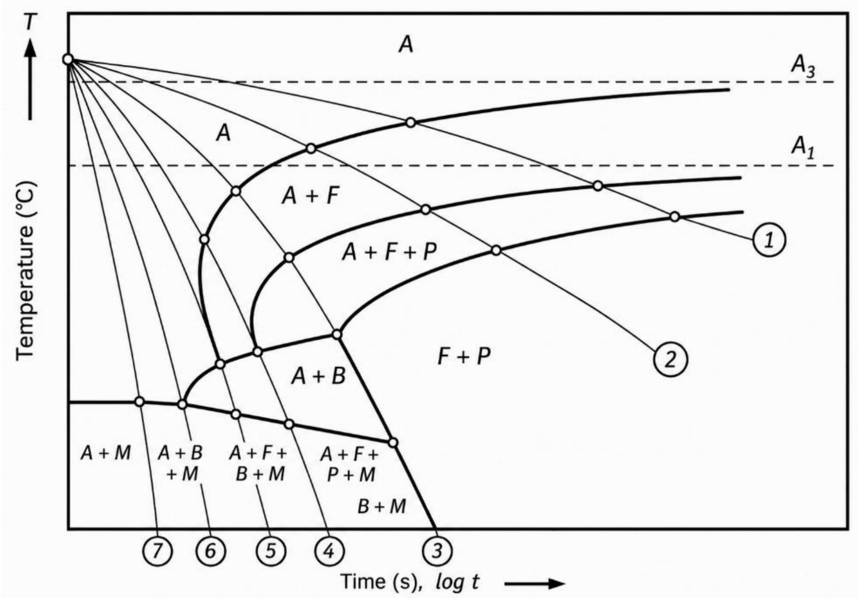


Figure 5. Theoretical continuous transformation diagram of a hypoeutectoid steel

The austenitization temperature and the critical transformation temperatures (A1, A3,) must always be indicated nn transformation diagrams valid for continuous cooling (T-lg(t) diagrams).

Transformations can only be analyzed using cooling curves at different cooling rates.

During cooling, equilibrium and non-equilibrium phases and microstructures can only form from austenite, and the formed microstructure does not change further.

> An austenitic transformation diagram only applies to a given chemical composition and initial austenitic state (homogeneity, grain size). After austenitization at different temperatures, with the same cooling conditions, the quantitative composition of the resulting microstructural elements, and thus the hardness of the piece, varies.

3. Heat treatments

The basic types of heat treatment processes are: annealing, stress relieving, normalizing, quenching, tempering, quenching and tempering.

Annealing

Annealing aims to set a state close to the equilibrium state. Steels with a higher (C>0.4%) C content can only be easily machined in the annealed state.

Method of implementation: very slow cooling from the austenite zone (A3 + 20-50°C) – in a furnace.

Stress relieving

The aim of stress relieving heat treatment is to reduce internal stresses caused by rapid cooling processes, in the case of parts susceptible to stretching or cracking during hardening, welding or forming.

It is carried out by heating from room temperature to 550-670 °C, holding for 2-4 hours, then slowly cooling.

Normalising

The purpose of normalizing is to restore the effects of changes in the microstructure of the material by complete or partial recrystallization, or to improve the strength properties of previously coarse-grained steel. The machinability of the normalized material is also better than that of the annealed state in materials with low carbon content. The mechanical properties of the material are often given in this state.

The method of implementation is cooling from the austenitizing temperature in still air. The holding time exceeds 30 minutes.

Quenching

Quenching aims to create a martensitic or bainite structure.

The method of its implementation is to cool the steel from the austenitizing temperature (A3 + 30-50°C) after full or partial austenitization at a cooling rate exceeding the steel's upper critical speed. Depending on the steel composition, the cooling medium providing the upper critical speed can differ (water, oil, or even air).

Tempering

Tempering aims to modify the quenched (hardened), brittle martensitic structure to increase resistance to dynamic stress and toughness.

The implementation method is to heat the part to the desired temperature after tempering, hold it there for a suitable period, and then cool it down. The material properties change depending on the temperature and the holding time).

During tempering at low temperatures (100-300 °C), the brittleness associated with the martensitic state can be reduced, while the hardness does not change or only slightly.

During tempering at high temperatures (500-680 °C), by breaking down the martensite, a fine carbide distribution and a significant increase in toughness can be achieved.

Quenching and tempering

Quencing and high-temperature tempering (550-650 °C) are called quenching and tempering. Its purpose is to give machine parts (shafts, gear parts) exposed to dynamic stress a ferritic-cementite structure, so that the material remains tough despite high yield strength and a significant fatigue limit. The structure obtained after tempering is spheroidal or granular pearlite..

4. Hardenability

One of the typical heat-treatment technologies for steel is quenching (hardening). Hardenability is the property of steel in which, when cooled from a temperature above A3 at a rate greater than the critical one, at least 50% martensite is formed in its structure, which increases its strength and reduces its toughness compared to the annealed state. In practice, the aim is for hardened steel to contain 100% martensite, in which case the hardening is called perfect.

Conditions of hardening:

- The carbon content of the steel exceeds 0.2%. → **C>0,2 %**
- The microstructure should be austenitic at the start of cooling → **$T>A_3+30–50$ °C**
- Cooling rate is greater than the upper critical rate → $\mathbf{v_{cooling}>v_{crit}}$

The hardness of martensite is determined by the amount of carbon dissolved. However, beyond a certain limit, increasing the carbon content does not increase the hardness of hardened steel; rather, it reduces it. In steels with a higher carbon content (above 0.6%), the completion temperature of martensite formation falls below 0 °C, so the austenite does not completely transform into martensite, but residual austenite remains in the steel. This is softer than martensite, thereby reducing the steel's hardness. In addition, if the hardening temperature is too low, the resulting microstructure is softer than martensite.

5. Hardenability

Hardenability is an important property of heat-treatable steels, which indicates the diameter of a cylindrically symmetrical piece at which martensite content is at least 50% along the axis of symmetry. This size is called the hardenable section diameter.

> The austenite grain size also influences the value of hardening. Coarse-grained steels achieve higher hardness, which means that increasing the austenitizing temperature can harden the steel to a higher level. However, this can easily lead to further damage due to the component's coarse grain size. Another influencing factor is the cooling medium, which affects the critical cooling rate.

Grossmann form

Grossmann introduced the concept that, under ideal cooling conditions (i.e., an infinitely high cooling rate), if the core of a round bar contains at least 50% martensite, its diameter is called the ideal critical diameter (D_{idcrit}). Taking the grain size of this diameter into account, the ideal diameter (D_{id}) is obtained. It is calculated according to equation 1.

$$D_{id}=8\sqrt{C}\cdot 1{,}08^{8-n}\prod_{i=1}^{m}\left(1+f_{Me_i}Me_i\right) \qquad (1)$$

where,
n – grain size number (unalloyed steel: 9, alloyed steel: 8),
Me – amount of alloys,
f_{Me} – multiplying factor,
Π – sum of products.

Without knowing the relative thermal conductivity, the real diameter can be calculated for the most common refrigerants using a simplified calculation based on equation 2, with the multiplication factors shown in Table 1.

$$D_{re}=\eta D_{id} \quad (2)$$

Table 1. Scaling factors required to calculate the real diameter

Coolant	η
water	0,75
oil	0,50
air	0,25

End-quench hardenability test– Jominy test

The end-quench hardenability test was introduced by Walter E. Jominy in 1937 at the General Motors Research Laboratory. The measurement setup (which is standardized, MSZ EN ISO 642:2000) is shown in Figure 6. A test piece of a specified size (Figure 7) is prepared from the starting steel material, which is heated to the hardening temperature, and then one of its ends is cooled with a water jet under specified conditions. The hardness of the thus-hardened test piece is measured longitudinally after it is machined to a flat surface. The cooling rate, and thus the hardness, gradually decreases as one moves away from the cooled end plate.

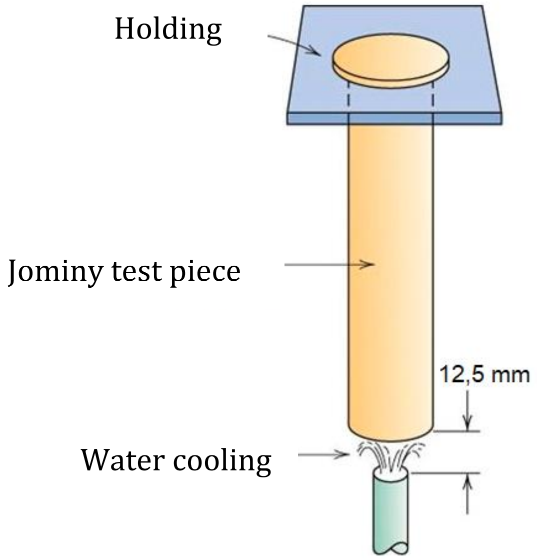


Figure 6. Arrangement of Jominy test

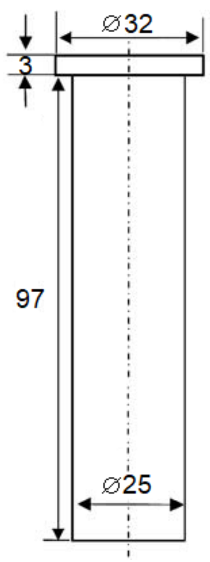


Figure 7. Sample of Jominy test

The specimen must be heated to the austenitic temperature, protected from oxidation and decarbonization, and then held at this temperature for 20 minutes. The heated specimen shall be secured in a vertical position on the stand of the cooling device by means of a flange formed on the specimen, and the specimen shall be cooled to room temperature by directing the water jet to the bottom of the end plate.

The side of the cooled specimen is ground along its component, resulting in a flat surface of about 10 mm. The piece must not heat up during grinding, as this would distort the measurement results. The hardness measurement must be carried out in specific steps, starting from the cooled end, initially at 2 mm and then at 5 mm, taking into account that the hardness changes rapidly near the cooled end. A continuous line represents hardness as a function of distance from the end face; this curve is called the Jominy curve. In Figure 8, two characteristic points of the curve are shown. Up to point A, the hardness is approximately constant, and at point B, the inflection point of the curve is found. Up to point A, the microstructure ideally contains 100% martensite, and at point B, 50% martensite.

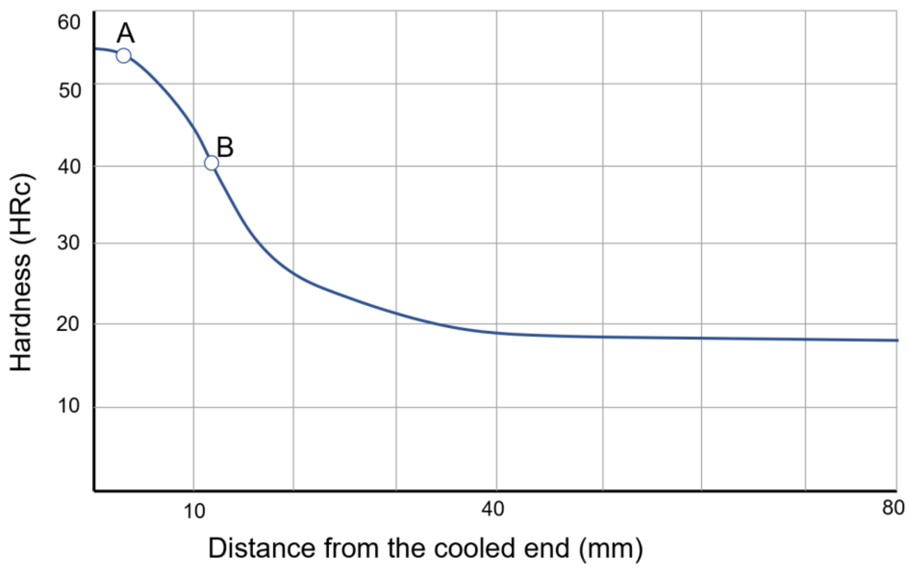


Figure 8. Jominy curve

By substituting the read A and B values back into the nomogram shown in Figure 9, the true hardenable section diameter is obtained.

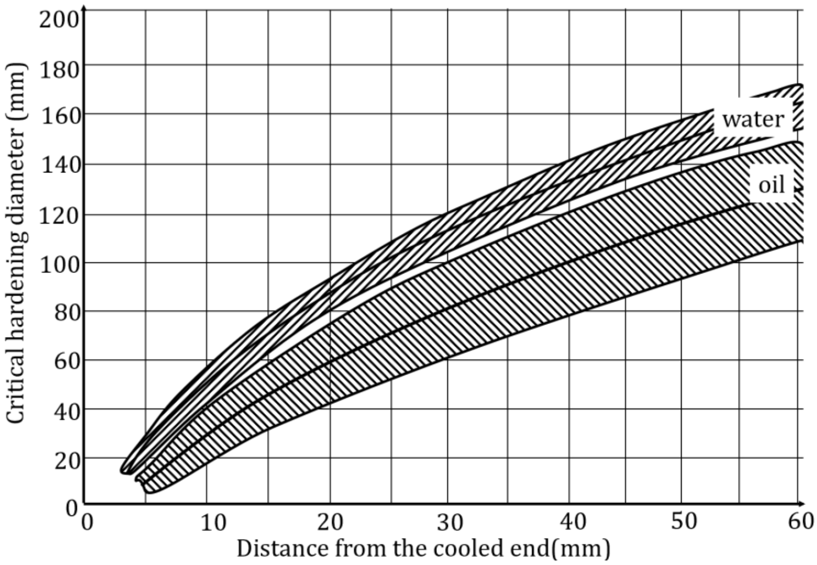


Figure 9. Determining real diameter given different coolants.

6. What to expect during the lab?

During the lab exercise, students calculate the ideal and realistic hardened diameters of C45 and 51CrV4 steels using the Grossmann formula. The results are compared after processing a real measurement series, and then conclusions are drawn between the theoretical and practical determination methods.

In the second half of the lab, everyone is given a heat-treated steel sample, and its hardness is measured. After that, they compare the results in a common table and draw conclusions about the relationships among hardness, carbon content, and heat treatment.

At the end of the lab, the resulting steel is subjected to bending.

The report must be completed during the lab and presented for signature.

Preparation questions:

1. Define the concept of heat treatment!
2. What are the basic heat treatment processes?
3. What is the difference between isothermal and continuous cooling?
4. What information can be read from a continuous cooling diagram?
5. What is the coolant in the case of annealing?
6. What is the coolant in the case of normalizing?
7. What is the coolant in the case of quenching?
8. What are the conditions for hardenability?
9. What is the meaning of the hardened diameter?
10. In what ways can the hardened diameter be determined?

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