TECHNOLOGY OF PRODUCTION
OF STEEL IN CONVERTERS

Didactic Text

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**Introduction to the subject**

Steel casting is an important part of manufacturing process. Today, a majority of steel is produced in the continuous casting machines and a smaller part is cast into ingot moulds. A relatively low proportion of steel is cast in foundries into sand moulds to form steel castings. The total steel production in the world currently amounts to around 1,240 million tonnes. In the Czech Republic, the total steel production is about 7 million tonnes and approximately 90% of the production is manufactured using continuous casting machines. The proportion of steel cast in moulds is about 8.5% and steel for castings about 1.5%. This text is to provide students with a support for the study of "Steel Casting and Crystallisation". At the end of the text, you will be provided with a list of references and recommended literature.

1. Casting house facilities

**Chapter sub-sections**
- Ladles, tundishes
- Equipment for handling ladles
- Ingot moulds, bases, head pieces
- Continuous casting machines

**Ladle**

It is a container of circular or elliptical cross-section, made of 25-40 mm thick steel plate, lined with refractory material. Ladle linings are currently made of either basic or high clay refractories. Ladle volume corresponds to the volume of steel produced in the basic production unit.

A ladle has a bricked cover preventing steel splatter and heat loss - see the picture

![Schematic of a ladle](image.png)

Ladles are handled using foundry cranes, manipulators, drying and heating burners - see the following figures.
The lower part of a ladle is provided with an outflow unit serving to discharge the liquid steel. There are two types of these mechanisms:

- A discharge opening consisting of a ceramic nozzle and a stopper rod (currently used in small steel mills and foundries)
- Slide gate - used in all small steelworks
These nozzles usually have a circular upper part of the inlet while the lower part takes different shapes. They are mostly made of magnesite, fireclay or graphite. The disadvantage of using nozzles and stopper rods is that they must be replaced after each casting. Besides, they do not guarantee perfect regulation of the liquid steel flow. In large steelworks therefore, only slide gates are today used.

This mechanism consists of an upper nozzle, top plate, bottom plate and a lower nozzle. The figure show a cross-section, and close-ups can be seen in the photos.
The gate is operated hydraulically. The ceramic part consists of a ladle brick, upper and lower nozzle, the upper one being fixed and the lower one is movable. The ladle brick is usually the same as for the stopper gate. The upper nozzle is situated in the ladle brick while the lower nozzle is in the sliding part of the gate. Slide gate plates are the most important part of the gate. They are exposed to the aggressive effects of steel as well as to sliding friction. The entire slide gate, including its mechanical part and holder, is a system which can be prepared outside the ladle. It can be very easily attached to the ladle using pins and wedges. Slide gate plates are mostly made of alumina or zirconia.

Schematic of a slide gate with: a) linear movement
b) rotary movement
Advantages:
- It allows high temperatures of steel with long times of processing
- Reusable
- Precise control of steel outflow
- Can also be used for the melting units

Tundish
Tundish is one of the technology units used in steel casting. Originally, tundish was used in the ingot casting method where a tundish was employed between the ladle and the casting system. It was used for the following technological and metallurgical purposes:
- it served as a storage of steel, e.g. when multiple heats were cast;
- it provided the control of the liquid steel mass flow into the casting system;
- it reduced the ferrostatic pressure of the liquid metal;
- it minimised the steel splatter;
- it made the temperature of the steel uniform during casting;
- it separated steel from slag.

Today, a tundish is primarily used in continuous steel casting systems where it is employed between the casting ladle and the mould. In continuous casting, tundish serves as a reservoir for the distribution of steel into individual casting streams and allows the ladle exchange by providing sufficient time without causing premature interruption of casting steel flow into the mould. Therefore, from the technological and metallurgical point of view, the tundish provides other important functions which significantly affect the casting process stability and the quality of strands, in addition to the above mentioned advantages.

Examples of tundishes used in continuous casting machines

A tundish consists of a welded steel shell lined with a multilayer refractory lining, which is the basis used for both types of steel casting. In this description, we only focus on tundishes used in continuous casting machines because their use is essential to ensure the continuity of sequential casting (i.e. casting heats sequentially). These tundishes are usually also equipped with features to affect the stream of steel in a tundish (e.g. impact pads, dams, weirs, etc.). The incoming stream of steel flowing from the ladle into the tundish is protected from re-oxidation using a ladle shroud. Furthermore, to reduce heat losses of the liquid steel and improve the heat balance of the tundish, they are often fitted with covers. The steel flowing from the tundish is usually controlled using a stopper rod or a slide gate. Also the steel flowing into the mould is protected from re-oxidation, using submerged entry nozzles. The following figure shows components which can be part of the equipment of the tundish of a continuous slab casting system.
From the metallurgical perspective, the tundish provides one of the last opportunities to affect significantly final purity and structure of the steel. Important factors which have a major impact on the required quality of cast steel include the method of filling the tundish, quality of the tundish refining flux, erosion of the tundish lining, internal arrangement of the tundish, modification of steel using cored profiles, filtration of steel, blowing inert gases into the tundish, etc. Properties of continuous cast steel can therefore be affected using various methods employed in the tundish and are collectively called the tundish metallurgy. This will be described in more detail when discussing continuous casting of steel - Chap. 10

**Ingot moulds**

Ingot mould is a cast iron mould with a round, square, rectangular or polygonal cross-section, in which liquid steel solidifies into a desired shape to be processed by rolling or forging as a steel ingot. The figure shows the most frequently used cross-sections of permanent moulds.

Based on their shapes, there are the following moulds:

- A - shape - for casting the rimmed steel
- V - shape - for casting the killed steel
Material for the production of permanent moulds

- Grey cast iron with lamellar graphite (3.3 ÷ 4.0 % C; 0.4 ÷ 0.9 % Mn; 1.2 ÷ 2.2 % Si; max. 0.2 % P; max. 0.05 % S)
- Ductile cast iron
- Treated pig iron

Mould pads
They are an integral part of moulds and are placed under the mould. Their material is the same as the material of moulds. They are exposed to intense stress, especially during casting metal in the first moments at the beginning of the casting.
The mould pads are shaped to avoid metal splatter. Their examples are shown in the following figure.

They are used for casting the killed steels and are designed to concentrate the shrink in the head portion of the ingot. The refractory portion of the shell is mostly made of cast steel and lined with (compacted) refractory material with low conductivity which helps to maintain steel in a liquid form as long as possible. Exothermic lining is sometimes used, especially when pouring very heavy ingots. The figure shows the arrangement of the refractory cap.
Continuous casting systems will be described in the following chapters.

2. Steel casting methods

Chapter sub-sections
- Basic classification of steel casting
- Casting into ingot moulds
- Continuous casting of steel

Liquid steel produced in steel-making plants is after tapping, deoxidation and other extra-foundry processing cast (castings, ingots, or products of continuous casting), and further processed in rolling mills and forges. When pouring steel into an ingot mould the liquid metal gets in close contact with the cool walls of the mould which results in a decrease in the temperature of steel and it becomes to crystallise. Nowadays, 9% of the total steel produced is cast into cast iron moulds, i.e ingot moulds, using this traditional method of casting steel, while 90% is cast using continuous casting machines. In developed countries, the proportion of steel cast in continuous casting machines (CCM) is almost 100%.

Casting steel into ingot moulds
It is performed in the cast house of steelworks. Cast iron moulds - ingot moulds - are placed either on mobile carriages or on a casting field. Steel is poured into moulds either directly from the tap ladle or via a tundish which is equipped with gates - top casting.

Schematic of top casting via a tundish is shown in the following figure.

In the bottom gating method, steel is not cast into moulds directly, but via a sprue and runners, and then it rises evenly in all ingot moulds simultaneously. For this casting method, moulds can also be placed on casting bogies or in casting pits. The shape of the moulds is based on the requirements of the rolling mills. A diagram of the bottom gating method of pouring steel is shown in the figure.
The advantages of the top casting compared with the bottom casting include lower labour demands and lower consumption of refractory materials for the preparation of the casting system (no removal of old casting systems and building new systems in the casting plates, etc.), lower loss of steel (particularly losses during bottom casting moulding resulting from the solidification of steel in the gating systems - so-called "bones"), better location of the heat centre of the solidifying ingot in its upper part, lower potential additional contamination due to a contact with the casting ceramic materials, lower temperature drop between the ladle and the mould, etc.

Drawbacks of the top casting compared with the bottom casting method include higher potential occurrence of some defects, such as scales, longer time interval for casting the ladle, higher number of ladle closures and therefore increased wear of the ceramic closing mechanism, poorer monitoring and control of the casting speed, higher wear of moulds, etc.

**Continuous steel casting**

There are two types of continuous steel casting systems. Vertical continuous casting machine consists of a tundish, mould, secondary cooling system with guide rollers and cut-off device. The design of this device has changed many times over the years. Nowadays, the most frequently used systems include the vertical CCM with bending or with bending and a curved mould - see the diagram.
The technology of horizontal casting is again based on pouring steel into a mould. Steel is fed from a ladle, the discharge of steel from the ladle into the mould and the whole further advance through the secondary cooling zone and the cut-off device is horizontal - **see diagram**.

![Diagram of a horizontal continuous casting machine](image)

1 – ladle, 2 – tundish, 3 – mould, 4 – secondary cooling, 5 – withdrawing rollers, 6 – cut-off device (torch), 7 – product, 8 – rolling table

The basic part of each CCM is a mould, which is a hollow copper mould, capable of cooling the steel to the solidification temperature as a result of intensive cooling by water. The steel is cast into the desired profile which is determined by the shape of the mould. The product coming out of the mould is already solidified on the surface, and it is further cooled in the secondary cooling zone throughout its cross-section. After passing through the draw rolls it is cut to length with a torch.
3. Steel solidification

Chapter sub-sections
- Nucleation process
- Homogenous nucleation
- Heterogeneous nucleation
- dendritic crystal growth

Nucleation process

The stability of gaseous, liquid or solid phase is determined by the thermodynamic conditions. The figure illustrates the dependence of the free enthalpy of the temperature (Ts is the melting temperature and Tv is the boiling temperature). Above the boiling temperature, the gaseous phase has a higher value of the free enthalpy than the melt while below the temperature of solidification the solid phase has less of the free enthalpy than the melt. The lower the free enthalpy, the more stable the system is, which means that the solid phase will be stable below the temperature Ts, while below the temperature Tv the melt is the stable phase.

The dependence of the free enthalpy on the temperature during phase change

Change in the free enthalpy $\Delta G$ in the transition from the melt to the solid phase is the driving force which determines the direction of the phase change. This basic thermodynamic phase transition condition is not sufficient because the actual start of phase change is determined by the kinetic factor. If a solid phase nucleus is not present in the melt, then it is possible to achieve high values of supercooling of the melt without crystallization occurring.

Homogenous nucleation

The change in the free enthalpy of a system during nucleation of the solid phase in the melt is determined by the general equation, and if a cube-shaped nucleus is involved, then:

$$\Delta G = l^3 \cdot \frac{\rho}{M} (G_s^0 - G_m^0) + 6l^2 \sigma$$

where

- $G_s^0$ ... is the molar free enthalpy of the solid phase,
- $G_m^0$ ... molar free enthalpy of the melt,
- $\rho$ a $M$ ... density and molecular (atomic) mass of the crystalline nucleus,
- $l$ ... edge length of the cube of the cubic crystalline nucleus
the interfacial tension between the nucleus and the melt.

For the critical size of a nucleus \( l_{krit} \) expressed by the edge length of the basic cube of the nucleus we derive
\[
l_{krit} = \frac{4\sigma M}{(G_l^0 - G_s^0)\rho}
\]

By adjusting this relationship, we can also derive the equation:
\[
l_{krit} = \frac{4\sigma T_{t\Delta} \cdot M}{\Delta H_{t\Delta}^0 \cdot (T_{t\Delta} - T)\rho} = \frac{4\sigma T_{t\Delta} \cdot M}{\Delta H_{t\Delta}^0 \Delta T \cdot \rho}
\]

The equations illustrate that for given \( T_{t\Delta}, \rho \) and \( M \), the critical dimension of the nucleus decreases with higher molar heat of thawing and the degree of supercooling \( \Delta T \) of the melt (or the degree of supersaturation of the melt with new phase nuclei) and with decreasing interfacial tension. These conclusions will also apply if spherical shaped nuclei are formed.

The dependence of a change in the system’s free enthalpy on the size of resulting nuclei according to the previous equation is shown in the following figure.

At temperature \( T_1 > T_{t\Delta} \), \( G_l^0 > G_s^0 \) and the value \( \Delta G \) grows steadily together with the size of the nucleus. When reducing overheating, i.e. if the temperature is near \( T_{t\Delta} \), the difference \( G_l^0 \) and \( G_s^0 \) will be smaller, and even if the functional dependence \( \Delta G = f(l) \) is more gentle, it will still increase steadily (curve \( T_2 \)). If nuclei are formed in a supercooled melt, i.e. if \( T_3 < T_{t\Delta} \) then \( G_l^0 < G_s^0 \), and in the functional dependence \( \Delta G = f(l) \) a maximum appears corresponding to the critical size of the nucleus \( l_{krit} \). The difference in the curve \( T_3 \) and \( T_4 \) is in relation with higher degree of supercooling and lower value of interfacial tension in the subsequently specified case (curve \( T_4 \)). Therefore, if the crystallisation nuclei of the new phase are to be stable, and if they are to be enabled a further growth, they must have a greater dimension than the critical dimension \( l_{krit} \). All nuclei with their dimensions smaller than the critical dimension are dissolved in the melt.

The next figure shows the dependence of the rate of nuclei growth \( \langle N \rangle \) on the degree of supercooling - for the conditions of homogeneous nucleation.
From the figure, it is evident that in this case it is necessary to achieve supercooling 0.2 $T_s$, which in practical terms means 250 to 300 °C. Such a degree of supercooling is unattainable in practical conditions.

**Heterogeneous nucleation**

Crystal nuclei are formed on solid particles which were present in the melt before reaching its critical supercooling. Heterogeneous nucleation is always involved in the crystallization of steel ingots. This is due to the presence of a large number of foreign particles (endogenous and exogenous inclusions). Heterogeneous nucleation is easier and it occurs at a much lower supercooling value, approximately 0.02 $T_s$, that is about ten times lower than in the case of homogeneous nucleation. In addition, formation of nuclei is helped by unevenness on the surface of the mould, which in terms of nucleation behaves like foreign particles in the melt.

In the presence of heterogeneous particles in the melt or unevenness of the inner surface of the mould, the energy required for the formation of nuclei is lower due to interfacial tension between the melt, foreign particles and the nuclei being formed.
Dendritic crystal growth
Steel crystallised in a dendritic way. The dendritic structure prevails where the melt in the vicinity of the phase interface has a negative temperature gradient. The growth rate of the dendrites depends on the degree of supercooling. In the longitudinal direction, dendrites grow a hundred times faster than in the transverse direction. The growth of dendrites is interrupted by connecting to another dendrite.

In metals, dendritic growth occurs when the rate of crystallization $v \approx 5 \text{ cm.s}^{-1}$ for heterogeneous nucleation and $v \approx 5,000 \text{ cm.s}^{-1}$ for homogeneous nucleation. A characteristic phenomenon in the dendritic crystallization is high crystallization speed $v$. The subsequent diagrams show the shape of the solid phase - liquid phase interface with positive and negative temperature gradients.

The following figure shows the dependence of the degree of supercooling on the shape of the interface between the crystals and the melt. It is obvious that small degrees of supercooling result in planar and subsequently cellular structure. Dendrites are formed only at high degrees of supercooling.

The next figure shows the dependence of the type of branching structure on the content of impurities, temperature gradient and rate of crystallization, illustrating also the shape of various stages of transition, from the flat plane of solidification to the formation of the cellular structure.
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4. Segregation in steel

Chapter sub-sections
- Microsegregation of steel
- Macrosegregation of steel
- The mechanism of exudates in a killed steel ingot

Microsegregation of steel
Steel ingots have internal discontinuities, they contain non-metallic particles of different chemical composition and size, as well as sites with different chemical composition of the steel. Differences of the metal’s chemical composition arise from limited solubility of accompanying and alloying elements in the steel during solidification. Accordingly, the resulting crystals inevitably have a different concentration of impurities than the original melt from which they were formed. The described phenomenon is generally called segregation, and it is called microsegregation because it concerns microvolumes. Steel always solidifies forming dendrites, therefore we often encounter the term dendritic segregation of steel, which means the same as microsegregation. Study of microsegregation is the basis for explaining the difference of the chemical composition of steel in macroscopic volumes, which was mentioned at the beginning and which can be therefore called macrosegregation. Microsegregation has a great impact on the quality of cast and formed steel. It is the basic process of heterogeneity formed in steel which can to some extent be influenced metallurgically by suitable composition of basic raw materials (e.g. by limiting the concentration of impurities), technology of production and casting, but perfect homogeneity of the steel product cannot be achieved. [1]

Equilibrium and effective distribution coefficient
The tendency of elements to segregate is expressed by the equilibrium distribution coefficient,

\[ k_0 = \frac{C_s}{C_L} \]

where
\[ C_s \] ... concentration of the element in the solid phase
\[ C_L \] ... concentration of the element in the liquid phase

which specifies different solubility of elements in liquid and solid steel.
Equilibrium distribution coefficients for various elements are shown in the following figure.

From the figure, it is evident that elements which have a low value of $k_0$ (oxygen, sulphur, phosphorus, carbon) have the greatest tendency to segregation (the difference between the content of the element in the liquid and solid phase).

The equilibrium distribution coefficient does not include the effects of the rate of cooling or flow velocity, therefore the effective distribution coefficient was introduced,

$$k = \frac{k_0}{k_0 + (1-k_0)e^{-\frac{\nu \delta}{D}}}$$

where

- $\nu$ ... rate of solidification, cm.s$^{-1}$
- $\delta$ ... thickness of the diffusion layer before the phase interface, cm
- $D$ ... diffusion coefficient of impurities in the melt, cm$^2$.s$^{-1}$

According to this relationship, the value $k$ increases (the segregation effect decreases) with increasing rate of solidification and decreasing flow rates (increasing value of $\delta = 1/\nu^n$).

The next picture shows the distribution of impurities in the melt and the solidified phase in different intensities of melt mixing. The thickness of the diffusion layer varies according to the intensity of mixing of the melt. In a perfect mixing, the value of $\delta = 0$ and the effective distribution coefficient will be equal to the equilibrium coefficient $k_0$. 
Constitutional supercooling

If a steady state in the plane of crystallisation characterized by equations applies to diffusion of impurities, then every point before the crystallisation boundary must have a known concentration of impurity, i.e. it also has a defined equilibrium temperature of isoliquidity by the respective binary diagram. Cooling of the molten metal leads to the formation of a temperature gradient $T$ in the melt which causes the temperature in certain places before the crystallisation boundary to be lower than the temperature of isoliquidity. This phenomenon is called constitutional supercooling.

Supercooling of the melt is essential for the formation of nucleation and the rate of nuclei growth. It affects the size of the crystals and primary grains. Formation of the supercooled melt zone before the melt-crystals interface causes instability of crystallisation, and it was shown that in the real alloys it is a condition for forming a branched structure of the dendritic and cellular type.

As shown in the figure, constitutionally supercooled melt zone starts forming from the point where the line giving the temperature gradient $\text{grad } T$ b) is the tangent of the curve of equilibrium temperatures. State c) already indicates that the actual temperature of the melt is lower than the equilibrium temperature (temperature of the liquidus).

The equilibrium and the actual temperature of the melt before the solidification plane: $T_e$ - equilibrium solidification temperature before the crystallization.
Conditions for the formation of a new phase by exceeding the threshold concentration of elements in steel

Microsegregation may lead to the formation of a new phase (gas, nonmetallic inclusions, etc.). In such a case, we have to, in addition to diffusion and mass balance, consider the reaction rate of the formation of the new phase and the corresponding equilibrium concentration of the impurity. If we denote the equilibrium concentration of impurity $C^*$, then:

- for $C^* > C_m$, a new phase will not be formed,
- for $C^* \leq C_m$, a new phases will form because the concentration of impurities on the interface $C_m$ will be higher than the respective equilibrium concentration.

In terms of crystallization kinetics and the impurity concentration distribution, we may distinguish three main options that are presented in the diagram. Figure a) shows a case when the formation of a new phase does not occur because $C^* > C_m$. Figure b) shows a change in impurity concentration only on the basis of diffusion, but because $C_m > C^*$ the formation of a new phase does not occur.

In figure c) as in the previous figure, the formation of a new phase does occur, but the distribution of impurities in the melt occurs both by diffusion and convection.

Macrosegregation of steel

Chemical heterogeneity with the level exceeding the dimensions of dendrites and primary grains is called macrosegregation. Larger areas with different content of impurities are formed through a process of microsegregation. Because during solidification of ingots and castings, typical areas form which have higher or lower content of elements in comparison with chemical analysis of the melt, this is referred to as a negative and positive deviation, or positive or negative segregation. As an example, we will discuss a steel ingot to see the consequences of macrosegregation processes. Segregation in continuously cast blanks will also be described in the following chapters.
The area of negative segregation is at the bottom of the ingot, and depending on the conditions of solidification its magnitude may differ. Positive segregation is usually found in the upper part of ingots and its maximum occurs in ingots of rimmed steel at a distance corresponding to about 80% of the ingot's height. Ingots of killed steels have the highest content of impurities in the head portion.

Clusters of solidified impurities of enriched melt between the dendrites, which are called exudates, are also typical for ingots and castings. Basically, these can be classified into two basic types of exudates, gap exudates (V-segregation) and rod-like exudates (A-segregation).

Positive segregations are mainly found in the upper and middle portions of the ingot and take a shape of A or V. The negative segregations occur in the bottom portion and take a conical shape.

**Negative segregation**

Solidification of ingots is accompanied by a reduction in the temperature gradient, therefore a decrease in the amount of heat removal and reduction of the rate of solidification. The effective distribution coefficient will decrease with the lower solidification rate. Before the solidification plane, crystals begin to form having lower impurity concentration than the surrounding melt. The crystals gradually advance into the central part of the ingot, and after reaching a certain speed the rates decrease according to the equation,

\[
v = \frac{8g(\rho_S - \rho_L)r}{3\rho_S \zeta}
\]

where

- \(\rho_S, \rho_L\) ... density of the solidified and liquid steel
- \(r\) ... crystal radius
- \(\zeta\) ... hydraulic resistance of particles in the melt.

**Positive segregation** (therefore also exudations) are caused by flowing melt in a two phase crystallization zone where volumetric shrinkage occurs during solidification and also thermal shrinkage. The flow is caused by different density of the melt, which arises as a consequence of microsegregation of impurities and accompanying elements. Findings show that depending on the initial chemical composition, density of the melt may decrease with decreasing temperature during solidification. In this case, the colder melt from the bottom of the ingot will ascend based on the natural convection.

Formation of channel segregations were successfully modelled using saturated ammonium chloride solution containing 30 wt % NH₄Cl and water - see the figure.
The mechanism of A-segregations formation
The figure below shows the upward flow of the melt in a two-phase crystallisation zone, enabling the creation of channels, caused by a decrease in the density of enriched melt in the bottom portion. In contrast, when the density increases with decreasing temperature, it leads to creating downwards flows, in which case the rod-like segregation does not occur.

- Surface tension of an enriched melt gradually decreases by the segregation of carbon and sulphur;
- The difference of surface tension between the basic melt and the enriched melt will be great and will increase during solidification;
- Enrichment of melt S and C, but also V decreases the density of the melt, leading to the production of immiscible phases in the shape of spheres rising to the upper portion of the ingot;
- When braked by the meshing of dendrites, the track of the enriched melt deflect towards the centre of the ingot;
- Elements with atomic number greater than iron (Ni, Mo, W) reduce the incidence of segregation.

Exudations of vacuum steel
- In theory, surfacing of the melt supports the surface tension difference of the basic melt and the enriched melt;
- Surface tension is most influenced by the presence of sulphur and oxygen;
- As a result of segregation, difference in oxygen concentration grows more in vacuum steels;
- It can be expected that the formation of segregations in vacuum steel will be easier.
Mechanism of V-shaped segregations
This type of segregations is formed in the axial portion of ingots and castings, and it has the characteristic shape of the letter V. Segregations are larger at the bottom of the ingot. If the taper of the mold is small, or if it is very slender (ratio H/D of the ingot), they may form in the upper part of the ingot as well. A characteristic feature is that the area around V-segregations has a lower content of impurities. This proves that the formation of V-segregation in the central zone of the ingot does not occur until the content of solid phase increases to 20-40% by weight, so that the melt cannot flow smoothly in the dendritic network. Shrinkage leads to the formation of tears which are filled with melt enriched with impurities flowing down diagonally from sites more distant from the ingot axis. The tear formation, as already indicated above, is caused by the forces induced by the effect of gravity and shrinkage during solidification and cooling of the ingot.
5. Solidification of ingots

Structure of the chapter:
- Calculation of ingot solidification
- Course of solidification of a rectangular ingot
- Solidified main portions of the ingot
- Structure of killed steel ingots
- Influence of some factors on the solidification of ingots

Calculation of solidification of ingots, rectangular ingot during solidification
The course of ingot solidification is indicated by the parabolic relationship between the thickness of the solidified steel \( \xi \) and the time \( \tau \) which is valid up to a distance of 0.75 \( R \) (from the surface of the mould)

\[ \xi = k \sqrt{\tau} \]

where
- \( k \) \ldots solidification constant 2.6 cm.min\(^{1/2}\)

Course of solidification of a round ingot can be determined from the following premise:
During solidification of a layer with a thickness of \( \xi \) and a unit height, the heat \( Q_1 \) is released:

\[ Q_1 = L \rho \pi \left( R^2 - r^2 \right) \]

where
- \( r \) \ldots radius of the liquid core of the ingot,
- \( L \) \ldots latent temperature of solidification
- \( \rho \) \ldots density of steel.

From the surface of the ingot, dissipated heat \( Q_2 \) is:

\[ Q_2 = \pi R^2 C \rho \left( t_p - t_0 \right) \]

where
- \( t_p \) \ldots surface temperature of the ingot,
- \( t_0 \) \ldots ambient temperature.

The relationship is valid for both round and square ingots. However, for a square ingot solidification, we must assume that in certain conditions solidification of one side will affect the other side.
This is based on the assumption that the advancement of the solidification boundary in the direction of the ingot’s diagonal, for a square ingot, has a constant speed.

If we name the thickness of the solidified steel in the direction of the diagonal \( (\xi_d) \), then

\[ \xi' = k' \sqrt{\tau} \quad (\text{pro} \ C = 0) \]

Index \( d \) denotes the diagonal direction.

Let us denote the orthogonal projection on the wall of the mould \( \xi \)

\[ \xi_o = k_o \sqrt{\tau} \pm C \]

The equation between \( k \) and \( k' \)is then

\[ k' = \frac{k_o}{\sqrt{2}} \]
The first figure illustrates a case where in a square mold the cooling effect of the adjacent side on the progress of solidification has not started yet. This effect will not start until the solidification in a direction of a diagonal projected at an angle of 45° on the wall of the mould reaches the selected starting point on the wall of the mould.

The second picture illustrates how in the next stage of solidification dissipation of heat begins via the adjacent wall of the mould.

1. If in the middle of the mould’s wall (i.e. the distance \(D/2\) from the edge of the mould) the inequality \(D/2 / \xi \geq 2.6\) is satisfied, there will be no acceleration during solidification due to an effect of the adjacent wall.
2. If \(2.6 \geq D/2 / \xi \geq 1.6\), there will be a gradual effect.
3. For \(D/2 / \xi < 1.6\), the progress of solidification is accelerated.

Solidification of the ingot head
In the ingot a shrinkage forms due to steel contraction during cooling and solidification. Ju. A. Nechenzi came up with the following equation for the size of the shrinkage

\[
V_s = \alpha_v + \alpha_m (t_1 - t_5) - \frac{1}{2} \beta (t_5 - t_2)
\]

where
- \(V_s\) ... shrinkage volume
- \(\alpha_v\) ... volume shrinkage coefficient during solidification (dimensionless),
- \(\beta\) ... volume shrinkage coefficient in the solid state,
- \(t_1\) ... mean temperature of liquid steel in the initial phase of solidification,
- \(t_2\) ... mean temperature of solidified steel in the final phase of solidification,
$$t_s \quad \text{... temperature of solidification,}$$

$$\alpha_{\Delta t} \quad \text{... volume shrinkage coefficient in the liquid state.}$$

This formula does not include solidification of the metal during casting, which is rather significant in the casting of ingots. Chvorinov specifies for the size of shrinkage the following:

$$V_s = \alpha_{\Delta t}(t_f - t_s) + \alpha_v \eta - \beta(t_f - t_2)\rho - \beta(t_s - t_2)\eta$$

where

$$1 - \eta \quad \text{... relative amount of metal solidified during casting}$$

$$t_1 \quad \text{... surface temperature of the ingot at the end of pouring,}$$

$$t_2 \quad \text{... surface temperature of the ingot at the end of solidification.}$$

The relationship not only takes account of the solidification of steel during pouring, but it also deals with the deformation of the solid crust. For different size ingots, the differences in volume of shrinkage can be explained by the deformation of the solidifies crust. The exact expression of the third term of the equation is, however, difficult. B. B. Guljajev modified the equation as follows:

$$V_s = \alpha_v + \alpha_{\Delta t}(t_f - t_s) - 0.5\beta(t_s - t_2)\frac{V_{i+h} - V_i}{V_{i+h}}$$

The index i refers to the body of the ingot and h to the head portion. The figure illustrates the volume shrinkage of steel during solidification depending on carbon content. The greatest shrinkage occurs when the carbon content is 0.50 to 0.70% and it is up to 4.2% of the volume. For steels with the carbon content of 0.2% the shrinkage is 3.5%. Shrinkage of steel from the temperature of superheating is small compared to the shrinkage during the phase change. In practical calculations we expect the overall shrinkage coefficient $\alpha_v = 0.030$ to 0.040 (i.e. 3-4%).

**Structure of killed steel ingots**

The following figure shows the internal structure of killed steel ingots. At the beginning of crystallization, due to quenching of the metal in contact with the mould, the casting forms its casting crust. These are tiny crystals formed at high cooling rates with large numbers of spontaneously arising centres which do not have time to develop. With increasing thickness of this layer, while heating the walls of the mould, conditions of heat dissipation change - geolithic crystals are formed.
The cooling rate decreases, but it is still sufficiently intensive to ensure the formation of columnar crystals. The growth of the crystals takes place until the temperature gradient of the liquid portion of the ingot at the boundary of steel solidification reaches the minimum value. Then the growth of columnar crystals stops.

The following is a zone in which the crystals due to the decreasing temperature gradient and the latent heat of crystallisation grow in all directions.

Influence of some factors on the solidification of ingots

The process of ingot solidification and the internal discontinuities are affected by a number of factors:

1. Shape of the mould (ingot)
2. Cooling rate (solidification)
3. Size of the ingot
4. Casting speed and steel temperature
5. Chemical composition of the steel

1. **Shape of the mould (ingot)**

A totally inappropriate ingot shape is when tapering upwards because the area of shrinkage porosity reaches very deep, often down to the bottom - see the figure. The moulds with high aspect ratio (slender) behave in a similar way. The slenderness determines the magnitude of shrinkage, axial porosity, distribution of segregation, ratio between the vertical and horizontal velocity of solidification - see the following figure. From the figure, it is clear that when the values $H/D = 2.6$, the height of the porous zone reaches up to 60% of the ingot body height. In the case of large ingots - at $H/D = 1.2$ - this height is approximately 40% of the total height of the ingot body.

The next picture shows a comparison of two types of forging ingots which shows the direct link between the mould bevel and the angle of "V" segregations

- Comparison of slenderness < 1.5; > 1.5
- Ingot's bevel <8%; > 8%
- The volume of the head <22%; > 22%
2. **Cooling rate (solidification)**
The effect of cooling rate is shown in the following figure. This effect has been illustrated by comparing segregations in ingots cast into ingot moulds and refractory moulds. Solidification of the ingot cast into the refractory mould took substantially longer, although it was the ingot of a medium size, the quantity and extent of rod-like segregations corresponded to those of a large ingot.

3. **Ingot size**
The quantity and size of rod-like (A) segregations grows with the increase of the weight of killed steel ingots. The idea of increasing segregation of elements depending on the weight of the ingot is shown in the schematic diagram and it is illustrated by examples in the table where analyses of different places in three different sized ingots cast from the same steel are provided.

The period of solidification increases with the increase in the cross section of the ingot, promoting the formation of inhomogeneity of the ingot, particularly intensity of the creation of the rod-like segregations A. At the same time, differences in the chemical composition between the head and bottom parts of the ingot increase.

4. **Casting speed and steel temperature**
The effect of temperature of the steel and casting speed on the formation of segregations is clear. The higher the temperature of the steel and the casting speed, the larger the size of segregations in the ingot. The temperature is also reflected in the influence on the type of excluded segregations. At higher temperature, the central gap segregations of the V type are more pronounced while at a lower temperature the rod-like segregations of the A type will be more abundant. The casting speed has a similar effect as the temperature.

5. **Chemical composition of steel**
Depending on the chemical composition of the steel, how much gas it contains, and also depending on the manufacturing method, the steel has a different degree of susceptibility to the formation of segregations. With increasing concentration of an element in the steel, the tendency of the element to be excluded in the form of segregations grows. The intensity of segregation of the element, with the other conditions unchanged, depends on the solidification interval. Phosphorus and sulphur are in the first place, both in terms of intensity of exclusion and in terms of harmfulness. Segregation of sulphur and phosphorus in segregations may reach 300%, according to some sources even 400%. Therefore, reducing the contents of these elements in steel is a major challenge in reducing segregations. The extent and intensity of segregations is also affected by the overall chemical composition of the steel which affects the area between the liquidus and solidus temperature, its range and therefore also the local solidification time. The shorter this period (less than the interval TL - TS), the lower the incidence of segregation.
6. Defects of killed steel ingots

Structure of the chapter:
- Surface defects (external)
- Internal defects

There are two types of defects:

Surface defects (external)
- external scales
- longitudinal tears
- transverse, skewed, or zigzagging tears
- cracks
- cold shuts
- superficial voids
- Slag and sand nodes on the surface

Internal defects
- Shrinkage and shrinkage porosities in the ingot body
- segregations
- flakes
- exogenous and endogenous inclusions

Further in the text, we will be discussing some of the most important of these defects.

Surface defects (external)

External scales
The top casting method of pouring ingots is accompanied by a splatter at the impact of the steel stream. The size of the splatter is given by the kinetic energy of the falling flow of steel, the shape of steel flow and shape of the lower part of the mould. Drops of steel which adhere to the wall of the mould rapidly solidify, and their surfaces may oxidize. Part of the droplets produced by the splatter which is closest to the level of steel has not enough time for oxidisation and are dissolved again in the steel melt. The slower the steel level rise, the lower the number of these droplets is. Although the dissolved amount of droplets increases with greater speed of casting, the splatter of steel increases too.

Unlike the top casting method, in the bottom gating method, scales may only be formed during pouring of the ingot. The figure shows how during fast pouring steel splatters on the wall of the mold. The larger the size of the ingot, the greater the risk of such scales.

Factors affecting the formation of scales:
- Non-centric casting
- The shape of the mould - more likely with slimmer moulds
- The height of the mould, which is related to the amount of the kinetic energy of falling steel (larger with higher moulds)
- Condition of the mould's walls
- Condition of the nozzle
- Improper regulation of pouring
- In the bottom gating method - wet runners

Ways of limiting scales
- Slow pouring
- Reducing the H-D ratio
coating the mould's walls
Use of mould pads
Quality nozzles with enabled control of the steel flow
For bottom gating - perfect drying of the casting system

Tears
Tears are widespread defects, belonging to the group of defects which can often cause damage of the entire ingot. Tears can be classified mainly according to the period of cooling in which the defect of the ingot is formed.
The first group contains the most widespread tears formed at temperatures close to the solidus temperature, i.e. during the solidification of the ingot or shortly after its solidification.
The second group comprises tears formed at lower temperatures than the steel temperature in the plastic state, and tears occurring mainly during phase transformations. These tears are more accurately called cracks.
The third group includes microtears formed in alloyed and high-alloy steels at temperatures of 1200-1300 °C and lower. Based on the shape, direction and position of the tears, they can be divided into longitudinal, transverse, variously oriented and internal tears.

The basic condition for the formation of a tear is tensile or shear stress which, especially at high temperatures, easily exceeds the strength of the steel after exhausting its plasticity. If the free shrinkage of the ingot is braked mechanically or thermally, or when unequal distribution of stress or creep occurs, whether in the entire ingot or just locally, these are the conditions for the formation of tears. Tears occur in virtually all steels and steelmaking, and are usually accompanied by segregations and ferrite bands, often also in connection with the occurrence of sulphide inclusions.

Internal tensions arise from mechanical restriction of free shrinkage, change of the volume by phase transition, or uneven cooling intensity in different sites causing uneven shrinkage. Ingots of killed steel with their clearly oriented crystallisation are most susceptible to tears. Ingots of semi-killed or rimmed steel are much less prone to tears.

Tears occurring during ingot solidification
After filling the mould with steel, a surface crust forms in contact of the mould’s surface with the molten steel. The steel's strength shortly after solidification is very low, as well as contraction - see the picture.

Once the shrinkage stress during braking, at least momentarily, exceeds the strength of the steel, or if there is initiation caused by inclusions, segregations or internal tears (as a notch effect), tears form with virtually no plastic deformation.
Formation of tears in this period is also closely linked with the development of a gap between the solidifying ingot and the mould. The mechanism of the gap formed between the ingot and the ingot mould is affected by these factors:

- a) chemical composition of the steel
- b) shrinkage coefficient of the steel,
- c) size of the ingot,
- d) shape of the ingot,
- e) casting rate and the way of pouring,
- f) steel temperature,
- g) condition of the internal surface of the mould.

The figure shows a schematic of the gap formed between the mould and the solidifying ingot.

![Diagram showing the formation of a gap between the mould and the ingot with labels for the mould and the ingot.](image)

Crystallisation of the ingot surface crust begins once the molten steel gets into contact with a wall of the mould. Shrinking of the surface of the solidified ingot is in the early stages of solidification compensated by plastic deformation of the steel. This period of ingot crystallisation is characterised by the fact that, due to ferrostatic pressure, the ingot crust expands together with the ingot mould, which in this period is associated with high plastic deformation. With further lowering of the temperature, the plastic properties of steel are reduced, and forces of the interaction in the solidifying ingot increase; the ingot crust's strength exceeds the plastic deformation of the crust and a gap between the ingot and ingot mould starts forming. In this period, when the strength of the ingot's crust is still low, but the crust has already lost contact with the mould, the conditions for the formation of tears are most favourable.

In the crystallization of the thin crust of the ingot, the following processes are underway at the same time:

1) Cooling and reducing the lateral dimensions of the ingot due to the solidification process of the steel.
2) Plastic crust spreading by the action of ferrostatic pressure.
3) Warming and expansion of the inner surface of the mold.

The process of creating a gap between the ingot and the mould is determined by the extent to which individual processes occur. If the plastic crust spreading is more pronounced than the contraction of steel and expansion of the mould, then the action of ferrostatic pressure deforms plastically the crust, holds the walls of the mould and the gap is not formed. With intensive cooling of the surface of
the ingot, solidification rate exceeds the rate of plastic deformation of steel, followed by a quick separation of the ingot from the mould.

When steel is poured quickly, with also ferrostatic pressure growing faster, the plastic deformation of the crust exceeds the shrinking process and the crust is pressed to the wall of the mould. For a period of about five minutes after the start of casting, the crust remains pressed against the wall of the ingot mould. Unevenness on the inner surface of the mould causes the shrinkage of the stiff crust to slow down, leading to surface longitudinal or transverse, or differently oriented, tears in the ingot. The formation of transverse tears is also supported by stretching of the mould, in particular in the longitudinal direction. This is why in the period until the formation of the gap between the mould and the ingot the tears form especially by braking the shrinkage of the solidifying ingot crust and expanding the walls of mould.

However, if the steel is cast slowly, then the gap between the mould and the ingot already forms during casting; the shrinkage of the thin crust of the ingot is not restricted by the mould wall and the ferrostatic pressure of steel at this point is not large enough to exceed the strength of the solidifying crust. In slow pouring, therefore, there are no tears, but there is a growing tendency to other defects, especially cold shuts.

Therefore, it is necessary to select an optimum casting speed at which the shrinkage of the ingot crust is compensated with its plastic expansion, and where contraction of the walls is not hindered by the walls of the mould. The optimum casting speed is dependent on many factors as mentioned above, such as pouring conditions, type of ingot, steel temperature, etc.

**Tears formed during cooling of the ingot - cracks**

Tears occurring at lower temperatures - during the ingot cooling - are less common, but if they do occur, they almost always indicate damage of the whole ingot. Cracks often extend the entire length of the ingot and reach deep into the ingot. They occur both on the outer surface of the ingot as well as inside. Cracks are formed only at temperatures below 400 °C, often even after cooling of the ingot. During the cooling period, the temperature of the outer layers of the ingot is always lower than the inner portion of the ingot. Therefore, during the temperature drop of the ingot breakdown of austenite takes place in different layers of the ingot in an uneven manner. When in the outer layer of the ingot the austenite breakdown is fully completed, in the adjacent inner layers of the ingot it is still under way, which is accompanied by increasing volume. At the same time the cooling outer layer is shrinking which leads to the formation of tensile stress in the outer layer. If the temperature difference between the outer and inner layers of steel is large, and if the steel is not sufficiently plastic to counterbalance the resulting stress, then cracks develop in the surface portion of the ingot.

**Inner intergranular tears**

Inner intergranular tears are formed during cooling of ingots of alloy steels, especially low-carbon chrome-nickel, chrome-nickel molybdenum and chrome-nickel tungsten and chromium-nickel-tungsten steels. They may occur in different parts of the ingot. They are either located in a spider-like manner inside the ingot without a more exact place determination (see the figure), or more often, they occur in the axis of the ingot (see below).
They are formed shortly after solidification of the inner part of the ingot, i.e. at temperatures of about 1,200-1,400 °C. Their formation is supported by the tension arising by rapid solidification of the inner part of the ingot and increased concentration of undesirable elements at the grain boundaries.

These tears are sometimes referred to as sub-microtears or intradendritic tears. Their formation is explained by the fact that during solidification of dendrites, melt with lower melting point is closed between axes of the dendrites and the shrinkage results in pores - sharp protrusions. At the end of solidification, individual dendrites shrink as well. Unless decrease in volume between the dendrites is replaced with melt, it leads to the creation of shrinkage porosity between dendrites, subsequently developing in tears.

**Cold shunts**
The main defects in ingots of killed steel, usually during bottom gating, include cold shunts, also referred to as cold laps.

During normal casting of killed steel by the bottom gating method the level of steel in the mould creates an oxidic coating associated with the process of the physico-chemical processes at the contact of molten steel with a wall of the mould and the gaseous atmosphere above the molten metal. The level of steel in the mould at the contact with the wall of the mould creates a convex meniscus whose height and shape depends on the respective surface and interfacial tensions, and on the size of the angle between the molten steel and the wall of the mould.

The formation of a cold lap begins by a crust being formed on the bent portion of the meniscus. During casting, the thickness and the surface of the crust increases while further rise of the level of steel in the mould increases the pressure on the meniscus until the pressure of the liquid steel bursts the crust and the liquid steel is poured over the crust. The crust formed on the meniscus has become so thick and rigid that it does not bend back towards the mould and the solidified surface contaminated with oxides welds with the molten steel. A cold shut is often accompanied by the presence of sand or slag spots and the formation of transverse tears or secondary shrinkage.

All precautions against cold laps must be carried out so that the meniscus of steel is as low as possible and steel at the mould level is as liquid as possible, i.e. the warmest, and oxidation of the steel is effectively suppressed. This can be relatively easily achieved by higher pouring temperatures and pouring rates. However, an increase in the temperature of steel and the casting speed leads to the formation of other defects.

![Formation of a cold shut on the surface of an ingot](image)

Formation of a cold shut on the surface of an ingot
In addition to the above factors, the occurrence of this defect will be also affected by:
- use and quality of coating of the mould
- use and quality of casting powders.

Slag and sand sites on the surface
Careless way of making the casting slab, runners cleaned insufficiently with air blasting, and also poor quality material of the runner bricks results in the steel catching the refractory material. This material then emerges on the surface and can settle on the wall of the mould where it is entrapped by the steel. As a result, there are sporadically occurring slag and sand nests on the surface of the ingots.

Superficial voids
Are a result of the presence of gas in the steel:
- oxygen
- nitrogen
- hydrogen
- carbon monoxide.

Causes of voids
- wet lining, channels, lining of the head extension
- defective inner surface of the mould and its modification
- inappropriate process of pouring
- high content of gas after treatment outside the furnace (mainly hydrogen)
- insufficiently deoxidised steel

Internal defects
Shrinkage and shrinkage porosities in the ingot body
The formation of shrinkage is closely related to reducing the volume of steel, already during the reduction of the temperature from the casting temperature to the liquidus temperature, and especially in the interval of solidification in the area between the liquidus and solidus.
The mechanism leading to shrinkage is often schematically illustrated as a process where a cooling effect of only the walls of the mould is assumed, and the progress of solidification is shown in different time periods, after which the remaining metal level repeatedly decreases until a void of approximately conical shape forms.

Schematic of the formation of shrinkage
a) mould filled with steel; b) beginning of ingot solidification; c) end of ingot solidification

Shrinkage in the ingot is always formed in the place where the metal remains in a liquid state for the longest time. Liquid steel is kept the longest in the heat centre of the ingot and from this place the
liquid steel is supplied, like from a reservoir, to the places where losses occurred during solidification of the volume. The heat centre of the ingot is typically at the top of the ingot.

In carbon steel, shrinkage and shrinkage porosity in ingots occupy on average 3.0 to 3.5%, which is less than the actual shrinkage of steel. Part of the reduction in the volume of steel by shrinkage is attributable to the overall shrinkage of the ingot while another part may take the form of interdendritic microcavities. In unaffected solidification of the ingot, shrinkage, and particularly its continuation along the axis of the ingot, leads to shrinkage porosity in that place.

Shrinkage porosity under the shrinkage is formed in the same way as the shrinkage during solidification of the last remains of steel, when there is not enough of liquid steel to fill the internal voids.

**Causes of shrinkage in the body of the ingot**
- unfavourable shape of the mould - required is a V shape
- slenderness of the mould - lower H/D ratio is better
- small bevel of the mould
- Incorrect casting temperature and casting speed
- small size and unfavourable shape of the head piece
- insulation of the head piece and cover insulating slag
- casting in an inappropriate way
- defective casting system
- insufficient time of the ingot standing in the mould

**Exudates**
- see the section describing ingot segregations

**Flakes**
The term “flakes” means transverse tears in the middle of formed products, expressed on a fracture as circular spots with shiny crystalline surfaces. They are caused by increased hydrogen content above a certain limit which is about 2 cm³. 100 g⁻¹ of steel.

In such contents, hydrogen will not be excluded in the form of voids, but it is dissolved in the steel in an atomic state. It is accumulated in small voids or pores of the ingot. With decreasing temperature, when its solubility decreases, atomic hydrogen passes to a molecular form, and low temperatures (generally <200 °C), where plastic deformation is no longer possible, lead to coin-like tears with a glossy surface.

Prevention of flake formation includes measures identical to measures aimed at reducing hydrogen content or performance of anti-flaking treatment.

**Non-metallic inclusions**
They are formed as products of reactions, both during production and during pouring, or they get into steel from the outside and cause the deterioration of mechanical properties, or they are the defect itself.

Depending on the origin, inclusions are divided into exogenous and endogenous ones. The exogenous inclusions arise either by corrosive or erosive action of the steel on the refractory material with which it comes into contact during the steel production process, i.e. in the furnace, trough, ladle, nozzles, channels, etc. They are particles of refractory material, sand, slag or incidental impurities.

If non-metallic inclusions occur in the physico-chemical reactions in the liquid or solid steel, they are called endogenous inclusions. They mainly consist of sulphides, oxides, nitrides, carbides and complex inclusions. Graphical representation of quantitative proportion of exo- and endogenous non-metallic inclusions in steel poured via the bottom gating method is shown in the figure.
Legend

I – endogenous non-metallic inclusions;
Origin of exogenous non-metallic inclusions
II – pouring runners (refractory);
III – insulation fill;
IV – material of head lining;
V – linings of ladles;
VI – tapping trough;
VII – material of the tapping hole;
VIII – caught furnace slag
7. Machines for continuous casting of steel

Structure of the chapter:
- Principle of casting steel in CCM
- Production and proportion of CCM steel in CR
  - Development and classification of CCMs
  - Vertical CCM
  - Radial (curved) CCM
  - Horizontal CCM
- Defining basic concepts of CCM
- Basic components of radial (curved) CCM
  - Ladle turret
  - Tundish
  - Mould - primary zone of cooling
  - Electromagnetic stirrer
  - Secondary zone of cooling
  - Cut-off equipment
  - Tertiary zone of cooling

Principle of continuous casting of steel
Continuous casting is a technology which replaces the current process of casting steel into ingots. Increasing use of this technology is caused not only by constantly increasing demands on the quality of steel, but also by economic and production related indicators.

This text was primarily based on the national textbook by the author L. Böhm et al: Continuous casting of steel [2].

The principle of continuous casting can be defined as a technological process, wherein liquid steel (we can say with the final parameters) is continuously processed into a cast product which may have different shapes as required for subsequent forming. Different shapes of the products and their terminology are shown in the following figure.

When casting in a CCM, first the processed steel is brought in a ladle from the secondary metallurgy and placed in the CCM into the ladle turret which allows manipulation with ladles for continuous replenishment of the tundish. Tundish is another part of a CCM used for the distribution of steel into different casting flows which bring the liquid steel into the mould which is the primary cooling zone.

The mould is made up of a copper shell which is cooled by water. This leads to the formation of casting crust which makes up a skin of the liquid core of the strand. This means that the cross-section of the strand, after exiting the mould, has a casting crust on the edges, while the liquid core remains in the centre. The semi-solidified product is continuously drawn from the mould, therefore the casting crust must be sufficiently compact and strong to prevent penetration of the liquid core through the casting crust. After exiting the mould, the strand passes to the secondary cooling zone where it is cooled in an adequate intensity, so that at the end of this zone it is solidified throughout the section. The last but one step is cutting the strand at the end of the secondary cooling zone to the desired lengths for subsequent processing in a rolling mill. Finally, the cast product is placed on the cooling bed, called tertiary zone of cooling, where it is cooled naturally by the surrounding air.
The following table is an overview of the CCMs used in the Czech Republic, specifying their users and the types of CCM.

<table>
<thead>
<tr>
<th>Company</th>
<th>Type of CCM</th>
<th>Producer</th>
<th>Commissioning</th>
<th>Number of strands</th>
<th>Capacity (t/year)</th>
<th>Moulds</th>
</tr>
</thead>
<tbody>
<tr>
<td>1Z, a.s.</td>
<td>Radial</td>
<td>CLESIM</td>
<td>1990</td>
<td>5</td>
<td>800 000</td>
<td></td>
</tr>
<tr>
<td>1Z, a.s.</td>
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<td>CONCAST</td>
<td>1994</td>
<td>8</td>
<td>1 200 000</td>
<td></td>
</tr>
<tr>
<td>ArcelorMittal Ostrava, a.s.</td>
<td>Radial</td>
<td>MANNESMANN DEMAG</td>
<td>12 / 1993</td>
<td>6</td>
<td>1 100 000</td>
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<tr>
<td>ArcelorMittal Ostrava, a.s.</td>
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<td>VAI</td>
<td>11 / 1997</td>
<td></td>
<td>1</td>
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<tr>
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<td>8 / 1999</td>
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<td>960 000</td>
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<tr>
<td>ArcelorMittal Ostrava, a.s.</td>
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<td>CLESIM</td>
<td>6 / 1995</td>
<td>1</td>
<td>720 000</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Moulds Tubular (mm)</th>
<th>Slab (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 to &lt;130</td>
<td>200 to 450</td>
</tr>
<tr>
<td>180 to 100</td>
<td>210 to 400</td>
</tr>
<tr>
<td>300 to 2640</td>
<td>200 to 650</td>
</tr>
<tr>
<td>350 to 780</td>
<td></td>
</tr>
<tr>
<td>300 to 2640</td>
<td></td>
</tr>
<tr>
<td>350 to 780</td>
<td></td>
</tr>
</tbody>
</table>

Examples of different types of cast products and their terminology.
Development and classification of CCMs
Based on their construction, continuous casting machines can be classified into several groups. The first group comprises vertical CCMs. The development of this basic design of vertical CCM led to its modification to form a radial (curved) CCM. This type of CCM represents a new group which was further developed and today it is a prevalent type of CCM used around the world, including the Czech Republic.

Specific requirements of small steel mills and demand for the production of quality steels led to the emergence of yet another construction group, called the horizontal CCM. This CCM is not widely used in the steel industry and it can be said that today its use is rather diminishing.

The latest development is the classic design of the radial CCM with the profile of a mould which is close to the final shape of the rolled product (e.g. I-beams) or a special CCM designed for casting thin strips where the mould is replaced with two cooled rolls between which steel is poured to obtain a thin slab.

**Vertical CCM**
The conventional vertical CCM is characterised by the arrangement of the main parts of the casting machine made up of a mould, guide rolls, secondary cooling, etc., vertically arranged - see the figure. In this type of CCM, initial solidification takes place in the vertical mould, then the strand runs downward along the vertical track where the product is exposed to secondary cooling. Solidifying of the strand throughout the section is completed on the vertical track. Then the strand is divided into transportable lengths. This cutting takes place during the vertical downward movement of the strand, therefore the cutting device is positioned below the drive rolls.
Through modification of this type, a vertical CCM was developed with bending of the strand when already solidified. In this case, CCM was supplemented by a bending roll or a section of bending rolls which bend the strand during its continuous casting process. The purpose of this type of CCM was to reduce the overall height of the CCM and also to provide favourable conditions for cutting of the material where the strand is cut only when moving in the horizontal direction, hence devices for collecting blanks have been simplified as well.

These types of vertical CCM were sporadically built back in the 1970s, and only in the need of production of high purity steel or steel prone to segregation during solidification, e.g. pipes for gas pipelines in arctic regions or rolling element bearing bodies.

**Radial (curved) CCM**

Radial CCM is characterised by placing the main parts of the casting machine along the casting curve where the strand is guided. In this type of CCM, solidification of the strand starts in the mould, then it runs along a downward, curved path where the strand is exposed to the system of secondary cooling and the complete solidification of the strand throughout the cross-section occurs either in the curved path, or on the horizontal path of the strand, according to conditions used for casting. Therefore, the straightening of the strand takes place either with a fully solidified cross-section or with the strand comprising a liquid core inside the strand.

This type of radial CCM can be divided into two basic types which were further developed according to the requirements and capabilities of individual steel plants. The first type is the radial (curved) CCM with a flat mould. In this type of CCM, the solidification starts in the flat mould, then it continues to the following vertical section where it gains a sufficiently thick wall thickness, and subsequently proceeds to the bending zone, where it is deformed into a curved shape. Another shape deformation of the strand, or straightening, is performed in the transition to the horizontal section of the track.

The second type is the radial (curved) CCM with a curved mould. In this case, solidification of the strand begins at the beginning in a curved mould, while in the following section of the descending path of the same radius the strand is not subject to shape deformation which occurs only in the transition to the horizontal portion of the track.
In the radial CCM, the metallurgical length (i.e. the length of the liquid core of the strand) is divided into different sections, between the downward curved track and the horizontal track, based on the modification of the radial CCM. This parameter is used to increase the casting performance by increasing the casting speed.

Benefits:
- Potential for high performance casting using large metallurgical lengths (large length of the liquid core with a higher casting speed),
- smaller building height and lower capital investment costs compared to building a vertical CCM,
- simpler machinery for cutting and transport of the cast product,
- lower failure rate, easy operation and maintenance of the equipment (horizontal arrangement).

Horizontal CCM
Horizontal CCM is intended primarily for smaller steel mills with a wide range of high quality steel. The basic scheme of this device is characterised by the arrangement of the components in a horizontal direction. The equipment was built in the 1980s in the Hradek u Rokycan steel plant, but it is no longer in operation. This type of CCM has not become very popular in the steel industry and is rather on the wane. It is also used in the casting of non-ferrous metals where it is employed due to different operating parameters and conditions.
Defining basic concepts of CCM

Casting speed - speed at which the strand leaves the mould. It depends on the cross-section of the strand and its dimensions and quality of the steel.

Metallurgical length - the length of the liquid core from the steel level to the point of complete solidification throughout the entire product.

Sequential casting - method of casting where the ladle is regularly exchanged to ensure continuous casting by replenishment steel from the ladle.

Yield - Use of liquid steel in the CCM for its casting of the cast product.

Casting format - by the cross-section of the product, CCM is divided into a slab, bloom or billet CMM.

Examples of the basic types of cast products

![a) square and round billet, b) bloom, c) slab](image)

Difference between blooms and slabs based on their cross-section

<table>
<thead>
<tr>
<th>Bloom</th>
<th>Slab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width / Height ≤ 1.5</td>
<td>Width / Height ≥ 2.0</td>
</tr>
</tbody>
</table>

Basic components of radial (curved) CCM

In the Czech Republic, only radial (curved) CCMs are operated, therefore only this type will be described here in detail. A continuous casting machine consists of several structural units which are connected and have different functions. These structural units, or nodes, consist of:

- an option of a ladle with a rotating turret or fixed base,
- a tundish with an intra-ladle car,
- mould with oscillation and the primary cooling circuit,
- electromagnetic stirrer - a modifier applicable as needed,
- secondary cooling system with guiding units,
- tertiary cooling with guiding units,
- withdrawing unit with a straightening unit,
- cut-off equipment
- labelling systems,
- exit for removal of the products with a cooling bed, etc.

As an example, here is a picture illustrating a section of a slab radial (curved) CCM to provide an idea about the location of the structural units.
Ladle turret
A rotary ladle turret is used to manipulate ladles over the CCM platform in order to replenish steel to the tundish from periodically transported ladles. Its operation can be divided into two main tasks:

- movement of ladles over the equipment of the casting platform in a horizontal plane along a circular trajectory,
- lifting and lowering ladles over the casting platform equipment.

These functions show that the use of the ladle turret consists in performing the casting sequences. The construction of the ladle turrets has been developing due to growing requirements for CCMs and currently there are several design solutions.

Example of a ladle turret in operation

Tundish
This part of the continuous casting machine is described in a special chapter.

Mould - primary zone of cooling
The mould is an important part of a CCM. It provides the primary cooling of the liquid steel. This process is associated with the emergence of a solid outer crust, while in the middle of the strand is a
liquid core. This is why the outer crust of the strand must be sufficiently strong to withstand the ferrostatic pressure, mechanical stresses and deformation after exiting the mould. The mould removes 20-45% of the total heat of the strand, so the uniformity of heat transfer not only affects the thermal stress in the mould, but also in the strand.

The main material for the production of the mould is copper because this material has high thermal conductivity. Copper alloys are also used, e.g. based on Cu-Ag, Cu-Cr, Cu-Zr, etc. These alloys exhibit greater durability than pure copper moulds.

Based on the construction, moulds can be divided into three basic types: bloom, tube and plate moulds. It is also worth mentioning a special group called curved moulds which allow significant reduction of the height of CCM.

The first type, the bloom moulds, are made from forgings with bores drilled into them for the passage of cooling water. This type is rarely used because large amount of copper is needed for its production. The remaining two types of moulds (tube and plate moulds) are composed of two parts, the inner part made of copper and the outer steel structure in which the copper part is inserted. A tube mould is therefore composed of a copper-made seamless pipe which is inserted and fastened in a steel casing. Such moulds are characterised by ease of temperature control (by changing the water flow), good thermal efficiency and simple construction. They are used for small, circular and square cross-sections of about 200 mm. The last type of moulds are plate moulds consisting of four plates joined in a steel frame. Nowadays, there is a modification of these moulds, called adjustable plate moulds allowing changes in the cross-section.

Tube and plate moulds are also divided according to their shape and size of the cross-section. There are a number of types and their basic classification is shown below.
Recently, a special type called convex moulds have been increasingly used. These moulds are characterised by their walls bulging out of the strand. This bulging, however, gradually diminishes in the direction of the strand and the walls are flat at the outlet of the mould. The bulging feature helps to ensure the dimensional accuracy of the strand during its solidification. This group of moulds is used in the casting of products with smaller dimensions, helping to increase performance of the CCMs by allowing higher casting speeds (5-7 m.min⁻¹).

An important parameter of moulds, called mould taper, represents narrowing of the mould's cross-section along its length. One needs to realise that solidification of steel in the mould is accompanied by the formation of a solid layer which keeps shrinking. Any loss of contact of this layer with the wall of the mould can lead to a failure of heat transfer and casting instability.

Shrinkage is primarily influenced by the chemical composition of the steel (mainly content of C), and therefore a mould with a certain inner shape (taper) is not suitable for multiple brands of steel, and it also affects its life. As the mould should support the casting crust along the whole length, and especially in the meniscus region and just below it, the taper should be adapted as much as possible to the shrinkage curve along its length.

One of the possible ways of eliminating the negative impact of various steel grades is their division into groups based on their theoretical taper and use of moulds with the appropriate tapers (although this can be challenging in the operating conditions). Another option is to replace the commonly used moulds with linear taper with moulds with parabolic taper, which will eliminate the unsupported area of the casting crust in the meniscus region and just below it, resulting in a reduction of heat removal disorders and instability of casting. This type of mould is also used for casting peritectic steels in which phase transformations occur during the solidification process.

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**Figure sl. 17 Distribution of tube and plate moulds based on their cross-section**

<table>
<thead>
<tr>
<th>Tubular (mm)</th>
<th>Plate (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 to 200</td>
<td>100 to 350</td>
</tr>
<tr>
<td>&lt;150</td>
<td>&gt;150</td>
</tr>
<tr>
<td>&lt;200</td>
<td>&gt;200</td>
</tr>
<tr>
<td>150 to 290</td>
<td>200 to 460</td>
</tr>
<tr>
<td>100 to 260</td>
<td>340 to 460</td>
</tr>
<tr>
<td>200 to 650</td>
<td>460 to 790</td>
</tr>
<tr>
<td>240 to 460</td>
<td>560 to 790</td>
</tr>
<tr>
<td>400</td>
<td>790</td>
</tr>
<tr>
<td>400</td>
<td>790</td>
</tr>
</tbody>
</table>

Sorting of tubular and plate moulds by cross-section
Another important parameter used to classify moulds is the way of mounting the mould in the CCM. Previously used stationary mounting was characterised by the strand moving in the firmly mounted mould, which easily lead to breakage of the casting crust. Therefore, movable moulds were developed, such as spring-cam or hydraulic moulds where the mould oscillates allowing detachment of the solidified crust of the strand to break from the walls of the mould, minimising the risk of breaking the crust and the formation of bleeding of the liquid core. This technique, or the movement of the mould, is called oscillation. In terms of the shape of the curve, we can distinguish the following types of oscillation:

- Sine - the downward and upward speed of the mould is the same,
- The downward speed of the mould is slower than upwards,
- The downward speed of the mould is faster than upwards.

The following figure illustrates the second case. The downward movement of the mould is slightly faster than the rate of the withdrawal of the strand, forming a process called negative stripping. It is followed by an upward movement of the mould, its speed being about three times faster than the speed of downward movement.

Legend:
1 - position during casting,
2 - position of the mould,
3 - stroke of the mould,
4 - downward movement,
5 - upward movement,
6 - negative stripping,
7 - final point of continuous downward movement.
Also in the case of the moving - oscillatory mould mounting, the core may break due to friction, which is minimised by using casting powders or oil lubrication. Casting powder is made up of dry, heat insulating fine-grained material, with a defined melting point, with the following functions:

- protects the metal from re-oxidation of steel in the mould,
- thermal insulation and protection against steel solidification on the surface,
- absorption and dissolved inclusions,
- lubrication and heat transfer at the interface between the steel and mould.

The effects of the casting powders in the fulfillment of the functions are dependent on the physico-chemical properties.

The casting powders are used for casting products of larger dimensions, while during casting of smaller products the powder is drawn into the mould, which affects the resultant steel cleanliness. Therefore, for smaller strands lubricating oils are used, namely vegetable oils such as rapeseed oil, etc. The lubricating oil is introduced into the upper part of the mould and one part of it is burnt on the surface, thereby preventing the access of air to the liquid steel. Another part will evaporate between the liquid steel and the wall of the mould, thus preventing wetting of the walls, and the last portion reduces friction between solidified layer of the strand and the wall of the mould.

Based on the nature of the cooling, mould can be divided along its length into:

- portion of direct contact of the metal with the wall of the mould,
- portion which forms a gap between the wall of the mould and the strand due to shrinkage (this portion is critical because between 80 and 90% of dissipated heat in the mould passes to cooling water there).

The transition of heat from the surface of the strand into cooling water in the event of gap being formed comprises the following components:

- heat transfer via a gas gap in the mould,
- heat conduction through the copper plate of the mould,
- heat transfer from the wall of the mould into the cooling water.

Therefore, the formation and characteristics of the gas gap have a significant effect on the heat transfer.

The mechanism of solidification and formation of the casting crust in the meniscus will be affected by the direct contact of the liquid phase with the mould wall, while it will also progress in the area of already solidified and by various influences formed meniscus. Therefore, it will not be a typical structure for direct and controlled heat dissipation through the mould wall, but the dendritic structure typical for solidification on a free surface. This confirms that the beginning of solidification of steel takes place in the area affected by surface phenomena, i.e. the area of the meniscus. This is where one can look for the cause of the oscillation wrinkles and also beginning of coming defects, both surface and subsurface ones.

The progress of heat flow in the mould can be demonstrated by comparing the heat flow density in the mould. It is evident that the heat flow density on the level, and above it, is low, followed by a strong rise after 2 seconds from the beginning of solidification, corresponding to the place 3-10 cm below the meniscus of steel, with normal casting speeds. Then the heat flow density gradually
decreases to a low value near the lower edge of the mould. This process of changes in the density of heat flow can be characterised as follows:

- Initially, the contact of the steel with the mould is limited to a relatively small place which is growing rapidly with the formation of the solidified casting crust,
- the observed maximum heat flow density is caused by the good thermal conduction contact of the casting crust which is pressed against the wall of the mould by the internal ferrostatic pressure,
- subsequently, as the casting crust becomes sufficiently self-supporting, a gas gap is formed between it and the wall of the mould. This phenomenon, along with the increasing thickness of the solidified casting crust, reduces heat flow density.

In terms of the way of heat transfer between the solidifying metal and the mould, the mould can therefore be divided along its height into three zones:

- **Zone \( L_1 \) –** place with the most intense dissipation of heat by conduction, metal has a direct contact with the wall of the mould, thin layer of the casting crust,
- **Zone \( L_2 \) –** place with an intensive flow of steel, air gap is partially formed here, which, however, is unstable - the thickness of the casting crust is already larger
- **Zone \( L_3 \) –** high thickness of the casting crust which should already withstand the ferrostatic pressure, a stable air gap is created - the heat dissipation is reduced up to five times.

Legend:
- \( a \) - liquid steel,
- \( b \) - solidified crust of the strand,
- \( c \) - gap,
- \( d \) - mould wall,
- \( e \) - cooling water,
- \( t_p \) - temperature of the strand,
- \( t_w \) - water temperature,
- \( q \) - heat flow density, \( \text{kW.m}^2 \).
In the zone $L_1$ which characterises the upper portion of the mould where the liquid steel is in direct contact with the mould wall, the value $q_1$ ranges between $2300 \div 2900$ kW.m$^{-2}$.

In the zone $L_2$ (transition zone), which is found below the zone $L_1$ and where a solidifying crust is already formed, the value $q_1$ is reduced, ranging between $1500 \div 1800$ kW.m$^{-2}$.

In the zone $L_3$, which characterises the lower part of the mould and where a constant gap is created between the solidified steel crust and the inner wall of the mould, heat dissipation further decreases and the heat flow density $q_1$ is $800 \div 1400$ kW.m$^{-2}$.

The equation for the heat flow density in the primary cooling area, between the solidifying strand and the cooling water flowing in the mould is as follows:

$$q_1 = \left( \frac{1}{\alpha_1 + \frac{s_k}{\lambda_k} + \frac{1}{\alpha_2}} \right) \cdot (t_p - t_v) = k_i \cdot (t_p - t_v)$$

where

- $q_1$ ... heat flow density, W.m$^{-2}$
- $\alpha_1$ ... heat transfer coefficient from the surface of the strand onto the inner surface of the mould, W.m$^{-2}$.K$^{-1}$
- $s_k$ ... wall thickness of the copper mould, m
- $\lambda_k$ ... thermal conductivity of the copper mould, W.m$^{-1}$.K$^{-1}$
- $\alpha_2$ ... heat transfer coefficient from the outer surface of the mould into the cooling water flow in the mould, W.m$^{-2}$.K$^{-1}$
- $t_p$ ... surface temperature of the strand, °C
- $t_v$ ... temperature of the cooling water in the mould, °C

This equation uses the value

$$k_i = \left( \frac{1}{\alpha_1 + \frac{s_k}{\lambda_k} + \frac{1}{\alpha_2}} \right)$$

where

- $k_i$ ... coefficient of heat transfer from the surface of the strand into the cooling water flowing in the mould’s channels, W.m$^{-2}$.K$^{-1}$

which is valid in the event that the wall of the mould is in direct contact with the molten steel and heat transfer is realized via the copper wall of the mould. This, however, is only an ideal case in practice which is only possible in the liquid meniscus of the steel - see figure a).

If a casting crust between the mould and the molten steel has been created, casting powder is present, or a gas gap, the heat transfer must be adjusted in accordance with the previous equation - see also figure b).

$$k_{II} = \left( \frac{1}{\alpha_1 + \frac{\xi}{\lambda_{cary}} + \frac{\Delta}{\lambda_{ox}} + \frac{\delta_m}{\lambda_m} + \frac{s_k}{\lambda_k} + \frac{1}{\alpha_2}} \right)$$

where

- $k_{II}$ ... coefficient of heat transfer through each layer, W.m$^{-2}$.K$^{-1}$
- $\xi$ ... thickness of the casting crust, m
- $\Delta$ ... thickness of slag, m
\[ \delta_m \] ... thickness of the gas gap, m
\[ S_k \] ... wall thickness of the mould, m
\[ \lambda_{\text{kur}} \] ... thermal conductivity of the solidified crust, W.m\(^{-1}\).K\(^{-1}\)
\[ \lambda_{\text{ax}} \] ... thermal conductivity of the slag, W.m\(^{-1}\).K\(^{-1}\)
\[ \lambda_m \] ... thermal conductivity of the gas mixture in the gap, W.m\(^{-1}\).K\(^{-1}\)
\[ \lambda_k \] ... thermal conductivity of the copper mould, W.m\(^{-1}\).K\(^{-1}\)
\[ \alpha_1 \] ... heat transfer coefficient from the surface of the strand onto the inner surface of the mould, W.m\(^{-2}\).K\(^{-1}\)
\[ \alpha_2 \] ... heat transfer coefficient from the outer surface of the mould into the cooling water flow in the mould, W.m\(^{-2}\).K\(^{-1}\)

In the gas gap between the solidified slag and surface of the mould, however, the heat transfer occurs not only by conduction, but also by radiation. Radiation has a negligible effect on the heat transfer coefficient when \( \delta_m \) is less than 5.10\(^{-2}\) mm. For larger values of \( \delta_m \) the effect of radiation increases, especially for higher surface temperature of the strand. The intensity of heat transfer through the gas gap is mainly affected by heat transfer by conduction (75%), exceeding heat transfer by radiation (25%).

Heat transfer by conduction is affected by the size of the gas gap \( \delta_m \) and especially the value \( \lambda_m \). The value of \( \lambda_m \) is determined by hydrogen content in the gas mixture since it has about eight times higher thermal conductivity than the other components of the gas mixture.

The gap between the strand and the wall of the mould varies depending on the distance along the length of the mould, the nature of the movement of the mould, the casting speed etc. The size of the gas gap between the strand and the mould wall is not constant. Its value is determined experimentally and ranges between 0.2 to 2.5 mm.

**Secondary zone of cooling**
The secondary cooling zone is located between the mould and the tertiary cooling zone. This zone constitutes the main coolant water which is used to spray the strand. The proper method of cooling in the secondary area is very important because it affects the quality of the strand in terms of internal and surface defects including the central segregation.

The strand which is formed in the mould is characterised by the gradual formation of surface crust, leaving the mould still with a liquid core. After exiting the mould, it is subjected to stress due ferrostatic pressure with the combination of tensile, bending and gravitational force, which causes mechanical stresses and deformation which can lead to tears. An optimal and efficient secondary cooling system must meet the following requirements:
- uniformity of cooling the surface of the strand,
- intensive cooling
- short time of contact of non-evaporated water with the strand
- controllable intensity of spraying.

Two basic types of cooling systems are used in the secondary cooling zone of the CCMs.

A method of cooling where water is used as a cooling medium, representing single component cooling systems. In this system, the coolant is mechanically or by pressure sprayed in the form of small droplets on the surface of the strand. The nozzles used to spray water differ in their shapes, which allows the sprayed surface of the strand to have various shapes, such as elliptical, circular, flat or annular. It is this shape of the showered area which can affect cooling of the surface of the strand.

In the secondary cooling zone, there are also withdrawing rolls which cause re-heating of the cooled
strand, thereby preventing this single component system from providing uniform cooling over the entire surface of the strand.

The second type of cooling system is represented by two-component cooling systems where cooling occurs by mixing air and water in various proportions of these components as needed. The mixture of air and water is formed inside a nozzle and exits the nozzle through nozzle jets which are, as in the previous case, differently shaped to achieve a desired area of the sprayed strand. The water mist in the form of microscopic droplets is directed perpendicular to the surface of the cooled strand. The liquid is evaporated and there is no uncontrolled dripping of non-evaporated water on the surface. The water-air cooling system removes the deficiencies of the still used straight nozzles, while other advantages and benefits include:

- uniform cooling of the surface of the strand across the width,
- short time of water presence on the surface of the strand.

### Cut-off equipment
Continuous casting strands must be cut to lengths based on the requirements of the downstream operations. Nowadays, two methods of cutting-off are used, torch cutting or shearing.

Multiple-strand CCMs of large capacities use automatic machines for **flame cutting**. Technical gases used mainly include coal gas, propane and natural gas. Cutting strands using flame cutting is often preferred simply because the strand emerges from the caster at a relatively low speed, and also because cutting of hot material is 3.5 to 4 times faster than cutting cold material. Modern cutting torches allow the cutting of not only smaller billets, but also thick slabs. Two torches are often used for cutting thick slabs.

### Examples of cutting strands using flame cutting

- a) cutting of strands using one torch
- a) cutting of strands using two torches
The second method of cutting off strands is performed by shears. They are mainly used in cutting stainless and high alloy steels. This method of cutting enables a reduction in material losses while shortening the cutting times, but the pressure of the shears causes deformation of the cross section of the strand in place of the cut. Cutting by shearing is done using a fixed shearing machine with a movable shearing system, or using mobile shears which move together with the strand.

**Tertiary cooling zone**

The end of technical and technological unit of the CCM is made up of tertiary zone of cooling of the products. Its basic technological units are the withdrawing unit with guide rolls and, in the case of the radial (curved) CCM, also straightening unit and cut-off device. Also a manipulating device with a cooling bed can be included. The heat contained in the strand is therefore dissipated into the ambient air, primarily by radiation and to a lesser extent by natural convection, followed also by conduction into the guide, draw, and straightening rolls and the cooling bed.

**Additional equipment of CCM: Electromagnetic stirring**

Electromagnetic stirring is one of the optional technologies which can improve the internal quality of the strand. The principle of this technology consists in providing electromagnetic field throughout the metal. It results in stirring, achieving thermal and chemical homogeneity together with directing the flow and surfacing of inclusions, preventing also the occurrence of internal defects in the strand.

The employment of an electromagnetic stirring device is in continuous casting machines designed in four different levels:
- in the mould,
- just below the mould,
- in the secondary cooling zone,
- at the end of the secondary cooling zone.

An important parameter influencing the effectiveness of this technology is the selection of the appropriate direction for stirring. Different magnetic fields are in use, such as rotary, linear and transverse. By proper selection of these types of magnetic fields, casting powders and non-metallic inclusions can be avoided.

![Effects of stirring in the mould (M-EMS)]()

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![Electromagnetic stirring methods](a) rotary  b) linear  c) transverse)
Rotary types of stirrers are used in the mould based stirring systems as these have favourable effect on surfacing of particles carried from casting powders. Linear type stirrers are used for stirring just below the mould. Their employment reduces the formation of internal tears, leading to improvement of the structure of the strand and preventing the formation of axial segregation. The rotary types, which reduce the formation of segregations, are used at the end of the secondary cooling section.

The effect of electromagnetic stirring can be seen mainly in:
- achieving better internal structure of cast products,
- limiting central segregation,
- improving the distribution of non-metallic inclusions.

**Effects of M-EMS on the prevention of central segregations for billet**

a) Axial structure without M-EMS

a) Axial structure with M-EMS
8. Function of a tundish in continuous casting of steel

Structure of the chapter:
- Tundish construction
- Refractory linings of tundishes
- Function of a tundish in continuous casting
- Shroud
- Tundish flux
- Optimising steel flow in the tundish
- Impact pads
- Weirs and dams
- Baffles with holes
- Ceramic filters
- Blowing inert gasses into the tundish
- Outflow unit
- Submerged nozzles
- Special technologies applied in the tundish

Tundish construction
Tundish is one of the most important technological nodes of the continuous casting machine and is used between the ladle and the mould.

A tundish is made up of a welded steel shell lined with a multilayer refractory lining and usually also equipped with components affecting the flow of steel in the tundish (such as impact pads, weirs, baffles, etc.). Furthermore, to reduce heat losses of the liquid steel and improve the heat balance of the tundish, they are often fitted with covers. A tundish also comprises a system to control the outflow of the steel which is provided by stopper rods or slide gates.
It means that, apart from the shell itself, a tundish comprises a number of other components and linings, including:

- ladle shroud,
- tundish cover
- operating and permanent refractory of the tundish,
- impact pad,
- weirs and dams,
- baffles with holes,
- argon stirring element in the bottom,
- stopper rods,
- tundish nozzles,
- slide gates,
- submerged entry nozzles (SEN).

From the list of the equipment, it is evident that there are many different designs of tundishes. The final way of employing the different components always depends on the operating conditions and the needs of each particular operation of the steelworks. Based on their construction, tundishes can be divided using the following basic criteria:
Based on the shape:
- rectangular,
- wedge shaped,
- delta-shaped,
- T-shaped,
- C-shaped,
- H-shaped,
- L-shaped,
- X-shaped, etc.,

Based on the volume:
- small-sized (up to 20 tonnes),
- medium-sized (20-40 tonnes),
- large-sized (over 40 tonnes)

Based on symmetry of the tundish
- symmetric
- asymmetric

Based on the CCM type
- billet,
- bloom,
- slab,
- for casting beam blanks,
- for casting strips,
- for the horizontal CCMs

Tundish lining tundish linings contribute significantly to the operational functionality and achieved purity of steel from continuous casting process. Tundish lining is divided into the permanent (non-working) and working (protective) lining. The properties of tundish working linings are very important as they affect not only the life of the outer lining, but a number of other factors. The lining of a tundish should have sufficient heat resistance and strength. Lining material should resist chemical action of the elements contained in the steel, erosion of the casting stream and effects of the slag. It should also have certain mechanical strength which is important when removing residues of the solidified metal. Based on the method of making the lining and the refractory material, there are two basic types of linings, conventional (warm) and cold lining systems.

**Conventional (warm linings)** consist of several layers. The first layer is the insulating component and it consists of insulating panels. The next layer is permanent (non-working) and is composed of refractory blocks or monolithic materials, either stamped or cast refractory concretes. On this non-working layer, it is also possible to apply a protective layer in the form of a sprayed coat, called shotcrete. This layer is several tens of millimetres thick and serves to achieve a closed surface and protection of the non-working layer against the effects of liquid metal and slag. An important requirement for the conventional lining is their preheating prior to use to a temperature of about 1100-1200 °C. This heating is performed after making the lining of the tundish, using special burners which are lowered into the tundish through openings in the cover.

**Cold linings** - two designs are in use. The first design consists of insulating plates placed on the classic basic lining and the second design is a combination of insulating panels with a filler of silica sand.
Refractories used for cold lining are based on fibrous materials with a low specific thermal conductivity. In the first design, the insulating boards are inserted into a commonly walled and dried tundish, the joints between the boards are filled with refractory clay. In the second design, the boards are stacked, using templates, along the side walls in the required distance from the tundish steel shell and secured with steel struts. The joints are then filled with fireclay material and the space between the steel shell and insulation boards is filled with silica sand.

Today, the tundish lining mostly consists of several parts. The first part comprises the insulating material which is placed on the outside of the tundish. The next layer is permanent, monolithic (permanent or also non-working) linings consisting of cast heat-resisting concrete. These monolithic materials are injected into the cavity between the metal shell and the tundish, and are subsequently dried with burners. The work (protective) layer is applied on this monolithic (permanent) lining. The final, or work (protective) layer of the lining consists of sprayed material, called shotcrete, which is renewed after each sequence, or also monolithic work (protective) lining consisting of loose material applied (by casting) into the cavity between the metal shell and the base (permanent) lining. Likewise, this monolithic work (protective) lining is renewed after each sequence.
Function of a tundish in continuous casting

In continuous casting, tundish serves as a reservoir for the distribution of steel into individual casting streams and allows the ladle exchange by providing sufficient time without causing premature interruption of casting steel flow into the mould. Therefore, from the technological and metallurgical point of view, the tundish provides other important functions which significantly affect the casting process stability and the quality of strands, in addition to the above mentioned advantages:

- allows the control of the mass flow rate of liquid steel into the mould,
- reduces the ferrostatic pressure of the liquid metal,
- uniform the casting flow velocity,
- minimises the splatter of steel,
- uniform the temperature of the cast steel,
- eliminate turbulence of the casting flow,
- separate from steel slag.

The listed functions of the tundish very often vary in their demands on its shape and volume. For example, if we enlarge its size, the conditions for surfacing of non-metallic inclusions are improved too, and also the supply of liquid steel during sequential steel casting increases. However, the period of continuous flow during filling and emptying the tundish is prolonged. Another example of different requirements is the achievement of intense stirring of the steel in the tundish, which supports its homogenisation, but is unsuitable for the separation of non-metallic inclusions.
From the metallurgical perspective, the tundish represents one of the last opportunities to affect significantly the final steel purity, because it is the last component of processing the liquid steel. This means that during the casting, the steel in the tundish may be contaminated with inclusions formed e.g. by taking the ladle slag and tundish flux, by steel reoxidation or by melting and erosion of refractory materials. If the tundish is to be used as a refining vessel, these sources of the steel contamination must be removed or eliminated. Therefore, the properties of the continuously cast steel can be affected using different methods which are collectively called the tundish metallurgy.

The most frequently used methods of tundish metallurgy include protecting the steel using inert gases against its re-oxidation. Furthermore, this also includes various configurations of the interior space of the tundish using weirs, dams, baffles, and differently placed porous blocks. Another place with an impact on the final purity, allowing however only a partial modification of the liquid steel is the mould. Here, the influence of subentry nozzles with different numbers and shapes of the discharge apertures is used. The above methods generally also belong to the tundish metallurgy methods.

Therefore, the most frequently used tundish metallurgy methods include:

**protection of the casting stream using:**
- ladle shrouds,
- submerge entry nozzles,

**tundish fluxes:**
- covering,
- refining,

**appropriate tundish linings:**
- working (protective)
- nonworking (permanent),

**adjusting the flow of steel in the tundish using:**
- impact pads,
- weirs and dams,
- baffles,

**filtration of steel using:**
- foam filters,
- strainer filters,

**blowing inert gases into the tundish:** using the argon stirring element

Recently, the use of electromagnetic stirring and electromagnetic brake is on the increase. It is designed to prevent effectively the formation of defects in cast products, e.g. the centerline segregation and penetration of non-metallic inclusions into the cast strand body.

**Ladle shroud**

Ladle shroud is designed to protect the cast steel flow from the ladle into the tundish and to prevent steel re-oxidation. Ladle shrouds are attached to the slide gate nozzle of the ladle and their ends are immersed in the steel. However, in the ladle shroud the surrounding atmosphere is drawn in during
casting due to negative pressure. To avoid this, inert gas is blown into the steel flow in the ladle shroud.

Examples of various types of ladle shrouds

Application of a ladle shroud during operation

There are many ways of protecting the casting steel flow, including different types of ladle shrouds into which the inert gas is blown. The figure provides examples of various methods of protection of casting flow from the ladle up to the mould by blowing an inert gas, using ladle shrouds, submerge entry nozzles, protection of casting flow solely by inert gas, and their combinations.

Various methods of protection of casting flow from the ladle up to the mould

Subentry nozzle
Submerged nozzle (shroud),
Swivel tube
Swivel tube
Pressure tube
Bellows barrier
Pressure tube
Liquefied gas

Comparison of different methods of casting flow protection - see the table, demonstrate that the most effective protection of casting flow is the use of ladle shrouds with argon injections. Positive effects of ladle shrouds include the protection of steel from re-oxidation, preventing the contamination of steel with exogenous non-metallic inclusions. When perfectly immersed, they prevent taking the slag by steel flow from the tundish surface into the mould.

Different methods of protecting the casting flow and the values of nitrogen content in steel

<table>
<thead>
<tr>
<th>Protection method</th>
<th>Increasing of nitrogen content in steel melt (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unprotected</td>
<td>14</td>
</tr>
<tr>
<td>Argon</td>
<td>7</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>17</td>
</tr>
<tr>
<td>Ladle shroud</td>
<td>10</td>
</tr>
<tr>
<td>Ladle shroud + injection of argon</td>
<td>5</td>
</tr>
<tr>
<td>Ladle shroud + convex gas + argon</td>
<td>5</td>
</tr>
</tbody>
</table>
**Tundish fluxes**

The use of tundish fluxes provides the assimilation of non-metallic inclusions which, during the steel being in the tundish, come up to the metal-slag interface and increase therefore the purity of steel in the tundish. In addition, the tundish flux acts as a thermal insulation of the steel surface and also helps to prevent secondary reoxidation.

There are two main types of tundish fluxes. The first is the tundish flux based on solid lose material which has a beneficial effect on the thermal insulation of the bath. These slags, however, have considerably worse properties with regard to the absorption of non-metallic inclusions and prevention of re-oxidation. Therefore, refining tundish fluxes were developed, which are used as a means for absorbing inclusions and also have suitable properties for preventing secondary re-oxidation. Today, at the surface of steel in the tundish, multilayer (dual-layer) fluxes are used, which consist of both the tundish flux (insulation) and refining flux.

The effects of tundish fluxes on the quality of continuously cast steel depend on physico-chemical properties. The most important parameters of tundish fluxes include:

- chemical composition,
- bulk density,
- granulometric composition,
- temperature of the beginning and end of melting,
- surface tension,
- melting rate.

The basic ingredients of tundish fluxes are oxides CaO, SiO$_2$, Al$_2$O$_3$, Cr$_2$O$_3$, TiO$_2$, MnO, MgO, K$_2$O, Na$_2$O. Fluidising additives are added, such as soda, fluorite, Na$_3$AlF$_6$. Flux can also contain carbon which is added in the form of graphite in an amount of 3-40% of the flux weight. The chemical composition of the flux is closely related to a parameter which determines the flux basicity. The flux basicity is very low and ranges from 0.01 to 1.

**Optimising steel flow in the tundish**

In the tundish, numerous processes take place which affect the final purity of steel. Therefore, it is important to create such type of flow in the tundish, which will ensure identical properties of steel in all casting flows, i.e. that the steel has the same temperature, the same chemical composition, the same purity in terms of content of non-metallic inclusions, and the same dynamic behaviour. For these reasons, it is necessary that each particle of steel remain in the tundish for approx. the same time and go through the same phases of flow during that time. An important information on the flow of steel in the tundish is the time for which a certain portion of steel remains in the tundish, i.e. the "retention time". Theoretical average retention time of steel in the tundish was calculated using the equation:

$$\tau = \frac{V}{Q_v} \text{ s}$$

where

- $\tau$ ... theoretical average retention time, s
- $V$ ... volume of steel in the tundish, m$^3$
- $Q_v$ ... volumetric flow of steel, m$^3$.s$^{-1}$

For the analysis of the flow of steel in the tundish, a hypothetical model is used, in which the volume of steel in the tundish is divided into three parts:

- a stirred volume,
- a volume with a piston flow,
- dead volume.
The stirred volume is closely related to its inlet part, where the kinetic energy of the casting flow from the tundish provides intense stirring of the steel. The stirred volume is followed by the area of steel flow with a piston flow. An important feature of the piston flow is a uniform bath flow in which no element of the melt overtakes another element. In this area, the steel flow has a laminar character and conditions for the surfacing of inclusions are created. There are also conditions in the tundish, in which steel flows very slowly. This area is known as the dead volume of the tundish. These areas of dead volume are the greatest danger for the local solidification of steel. Therefore, it is important to minimise the size of the dead volume in the tundish.

Typically, the flow of steel in the tundish is associated with a dispersion of retention times, which means that some of the elements of the melt remain in the tundish longer while the other ones remain there shorter than the average retention time. The character of steel flow in the tundish should therefore meet the following requirements:

- minimum variance of the steel retention times for each nozzle,
- sufficient absolute values of retention times,
- minimum incidence of dead volumes,
- preventing short-circuit flow,
- maintaining a certain proportion of stirred volume of steel in the tundish,
- ensuring a sufficient proportion of the volume of steel flowing by piston flow.

During the use of tundish, it is necessary to maintain a certain minimum level of steel to prevent vortices in the area of nozzles, which would result in taking inclusions and flux into the discharging steel. Flow of steel towards each nozzle can be affected by installing suitable partitions, while taking into account that these partitions may increase the proportion of dead volumes and, when using materials of inadequate quality, they may become a source of further contamination of steel.

The bath flow in the tundish can be significantly affected using several methods. The entire shape of the tundish can be optimised, which is sometimes very complicated due to technical reasons. A simple and frequently used method is a modification of the internal configuration of a tundish, i.e. the insertion of various objects into the tundish volume (weirs, dams, baffles, etc.) which improve the character of the flow in the entire tundish in a suitable way.

**Impact pads**

Impact pads are placed into the tundish in the area below ladle shroud. They prevent the spatter of steel during filling the tundish, reduce the turbulence of the bath flow in the tundish and create a more suitable type of steady flow. At present, the impact pads provide a simple substitution of complex weirs and dams which are difficult to install. By installing an appropriately shaped impact pad, placed on the bottom of the tundish below the ladle shroud, the optimum flow of steel can be achieved, as shown in the figure.
The effects of the use of impact pads in the tundish can be summarized in the following points:

- increased purity of the cast metal,
- simplified structure of the tundish (elimination of dams and weirs),
- longer sequence,
- increased productivity,
- improved quality of cast products.

Impact pads may have different configurations, but they have several common features. The walls of the impact pads are usually in their upper parts tilted inwards so that the flow from the ladle, dispersed along the casting pad, is directed back to the middle of the flow. Impact pads can have various brand names, such as Turbostop (FOSECO), Preventur Pad (COMAT), Cushion Pad (Advent), Impact Pad (RHI), etc.

**Weirs and dams**

To modify the character of the steel flow in the tundish, partitions are often used, which are also referred to as weirs (upper partitions) and dams (lower partitions). They are designed to uniform the flow, eliminate dead areas and in particular to eliminate the short-circuit flow. Achieving this state leads to the creation of better conditions for the removal of non-metallic inclusions and improvement of the temperature and concentration homogeneity of the bath in the tundish. Their influence on the flow is shown in the diagram.
An important condition which must be taken into account is that the optimal variants of the shape and configuration of the partitions are designed based on model research. Optimal solution for a certain type of the tundish may not be optimal for a tundish of a different design.

**Baffles with holes**
Baffles include various types of partitions vertically placed in the tundish which exceed the height of the bath, have various thickness and are made of different refractory materials. The basic characteristic of the baffles is that they have a lot of holes of different diameters, shapes and inclinations, through which the steel flows during casting to the nozzles in the tundish.

![Different types of baffles](image)

Each baffle which is placed in the tundish fundamentally changes the character of the bath flow. In the area behind the baffle, where the bath flow has a directed character, conditions facilitating easier surfacing of non-metallic inclusions are created, which can affect the purity of steel. Baffles are also used for filtration of steel in the tundish, which also determines the purity of cast steel.

Designing the optimum variant of baffles is quite a complex task, because it depends on the tundish shape, bath height, flow over the baffle (and therefore the casting speed) and other parameters. In the design, placement of baffles must be optimised, their thickness and mainly the parameters of the holes (diameter, shape, number, inclination).

**Ceramic filters**
Filtration of steel is one of the ways which can significantly affect the cast steel quality. Filters must be able to capture non-metallic inclusions and other impurities while not providing too much resistance to the melt flow. Since the tundish is a large reservoir of liquid steel, ceramic filters must have a high thermal shock resistance and mechanical strength in heat, as well as a resistance to metal and slag impacts. Several types of ceramic filters are used for the filtration of steel in the tundish.

The most frequently used filters include the foam or multi-hole (strainer) filters which are placed in the vertical baffles which include 5-20 foam filters, and these partitions separate the tundish impact site (i.e. the place of the inlet of steel from the ladle) from the region of the nozzles.

**Blowing inert gases into the tundish**
Inert gas is fed into the bath through porous bricks located mostly in the bottom of the tundish. These elements are of utmost importance, as they should maintain their functionality during the entire casting process, which in practical conditions is casting a higher number of melts in a single
sequence. The gas coming from the block acts as a partition placed in the bottom of the tundish and directs the flow of steel to the slag-metal interface. A higher degree of removal of non-metallic inclusions is the result of three mutually acting mechanisms:

- directing the bath flow towards the surface of the tundish,
- better coalescence of inclusions, consequently increasing the speed of their surfacing,
- capture of inclusions on the surface of the blown gas bubbles which rise up to the steel surface and pass through the slag layer in which the inclusions are entrapped.

Example of location of a porous block in the tundish to form a bubble wall

![Example of location of a porous block in the tundish to form a bubble wall](image)

Example of the impact of the intensity of blowing the gas to form a bubble wall

a) intensity of blowing the gas - 5 l.min$^{-1}$

b) intensity of blowing the gas - 30 l.min$^{-1}$

![Example of the impact of the intensity of blowing the gas to form a bubble wall](image)

Monoblock stopper rod with stopper mechanism serves as a regulating and closing system of the tundish. In addition, the bottom of the tundish houses a nozzle which controls the amount of molten steel supplied from the tundish into the mould. The nozzle in the tundish is followed by submerge entry nozzle which leads the steel flow from the tundish into the mould, protects the steel flow against gassing and prevents the spatter of the metal. The slide gate system has a similar design. It consists of a well block, tundish nozzle, slide gate and submerged entry nozzle.

Examples of various configurations of a tundish discharge unit using stopper rods

a) stopper rod + tundish nozzle + subentry nozzle

b) stopper rod + well block + subentry nozzle

c) stopper rod + subentry nozzle

![Examples of various configurations of a tundish discharge unit using stopper rods](image)
The discharge unit consisting of a three-plate slide gate of the tundish

a) diagram of a slide gate  

b) example of a slide gate in operating conditions
Submerge entry nozzles

Submerge entry nozzles (tubes) perform essentially the same tasks as ladle shrouds, but they supply the steel flow from the tundish to the mould. Important functions performed by submerge entry nozzles include:

- protection of the casting stream against gassing (the re-oxidation of steel),
- prevention of metal spatter,
- feeding steel into the mould by laminar flow and making the metal distribution uniform in the cross-section of the mould,
- prevention of entrainment of casting powder and non-metallic particles from the surface into the mould,
- facilitates the wash-up of inclusions.

The shape of the submerge entry nozzle (tube) significantly affects the quality of cast products. According to the shape of the mould, the subentry nozzles can have various shapes, such as circular, oval, with a strain or non-strain end.

When using the submerge entry nozzles (tubes), inert gas is blown into the subentry nozzle. The aim of injecting an inert gas is the prevention of secondary oxidation and gassing the steel flowing from the tundish to the mould. There are many methods of protection of cast steel, which include various types of submerge entry nozzles, tubes and elements for blowing a protective gas. Submerge entry nozzles provide not only the protection of steel against gassing.

Subentry nozzles (tubes) also affect the flow of steel in the mould, affecting the purity of continuously cast steel. The parameters affecting the purity include size, shape and inclination angle of the outflow channels with non-strain end, but also the size of the tube cross-section at the inlet and outlet. In addition to these parameters, also the depth of the subentry nozzle immersion into the steel in the mould has influence. All these parameters affect the steel flow in the mould and thus the casting powder behaviour on the surface, its potential entrainment and surfacing of nonmetallic inclusions and their capture, but they also affect the formation of the casting crust.
Steel casting can also be performed without the subentry nozzles (tubes), which is called the open casting, and it is associated with a higher risk of re-oxidation during the free discharge of steel into the space because the steel flow is usually not continuous. This casting method is mainly used for lower quality steel, which has less strict requirements for the gas content in steel and also when using small cross-section moulds.

**Special technologies applied in the tundish**
The above tundish technologies can be considered as basic. These technologies are used in various combinations as required by each steel mill and steel production range. However, a tundish can also be supplemented with special technologies designed to increase the functional properties of continuously cast steel.

**Microalloying steel in the tundish**
The tundish is a device in which you can modify the chemical composition of steel bath using alloying additives. To achieve complete dissolution of alloying elements and thermal and chemical homogenisation of steel in each casting stream, optimum steel flow in the tundish must be ensured. Microalloying can be performed by adding a cored profile which is "shot" into the tundish at a certain speed to reach the required depth in which there are favourable conditions for the dissolution of alloying additives. This operation is carried out, for example, through a hollow stopper rod (see the figure) or directly into the steel volume.

**Modification of inclusions in the tundish**
During steel casting and particularly during long casting sequences, hardly meltable aluminates may be formed which cause a number of problems. Most important of these problems are the encrusting...
(obstruction) of the tundish subentry nozzles. These adverse effects mainly occur in aluminium-killed steel.

To prevent adverse effects of aluminate inclusions, modification of steel using calcium is used (most frequently CaSi). The favourable effect of calcium is that the resulting oxide CaO lowers the melting point of Al₂O₃, so the complex calcium aluminate inclusions are at normal casting temperatures in a liquid form and have a spherical shape.

**Reheating the steel in the tundish**
When applying tundish metallurgy methods, a certain cooling of the bath occurs. The reduction of steel temperature in the tundish is also affected by a lining which accumulates part of the heat from steel, mainly at the beginning of steel casting. Therefore, one of the basic prerequisites for the production of high-quality cast products is the achievement of optimal steel overheating above the liquidus temperature and maintaining that temperature during the entire casting process. Currently, the temperature correction can be achieved by reheating the steel, which is most often performed by induction reheating, most often carried out using induction or plasma.

Application of the above technologies of reheating steel in the tundish provides:
- energy savings resulting from the reduced overheating of steel during the melting process,
- longer life of production units and ladles due to reduced tapping temperature,
- small range of steel temperatures in nozzles, which allows the production of steel of a high purity and fine-grain structure.

When using any of these reheating methods, an essential condition for heating the steel in the tundish must be met, i.e. the uniformity of temperatures in all parts of the tundish must be ensured so that steel of the same temperature is delivered in all streams. In the Czech cast houses, these
methods are not used. The cooling of steel in the tundish during casting is prevented by the appropriate use of insulating slags and tundish lids.

Example of plasma reheating in operating conditions
9. Benefits of continuous casting of steel

Structure of the chapter:
- Comparison of production using conventional casting into moulds and casting in the CCM systems
- Comparison of metal yield from conventional casting into moulds and casting in the CCM systems
- Comparison of energy consumption for conventional casting into moulds and casting in the CCM systems

When compared with the conventional casting of steel into moulds, the benefit of the continuous steel casting can be summarised in the following points:
- higher metal yield
- energy savings
- lower processing costs
- lower investment costs

When comparing all phases of the production using continuous casting and casting into ingot moulds, we can see that the process technology is significantly simplified and also the production cycle is much shorter.

For example, the average difference in the slab yield - in relation to liquid steel - between the casting into ingot moulds and the continuous casting is approx. 15%, which is mainly due to the difference in the solidified steel losses.
- remaining steel in the tundish
- head and foot waste
- scales and cutting losses
- proportion of sequential casting
- losses in treatment plants

The first three factors are essentially not affected by the CCM concept. The type of the system, however, has a very effective impact on the last two factors. The proportion of sequential casting is directly dependent on the overall economic efficiency of continuous casting.
The next picture is a comparison of the energy consumption of both casting methods.

**Comparison of the energy consumption between the continuous casting method and the conventional casting method.**
Comparison of different energy consumptions in both casting methods and a comparison of the total costs are shown in the following diagrams.

The lower processing costs for the CCM are mainly a result of a lower number of operations when compared to the conventional casting into ingots and rolling the slabs. The ingot route requires, apart from casting, further operations such as stripping, inspection and surface treatment, heating in soaking pit furnace and rolling. The subsequent handling, treatment and storage of slabs are nearly identical for both technologies. The lower number of production operations in the CCM system generates the following savings:

- ingot route is more energy-demanding
- ingot route requires more maintenance
- ingot route requires higher depreciation
- ingot route requires higher wages costs
10. Defects of continuously cast products

Structure of the chapter:
- Surface defects
- Internal defects
- Shape defects

Surface defects of concast products:
- longitudinal tear at the edge of the cast product;
- longitudinal tear on the surface and near the centre;
- longitudinal tear on the front side close to the edge with accompanying longitudinal depression;
- transverse cracks on the edges;
- transverse cracks on the front side;
- transverse surface recesses;
- bleed, liquid steel exudation;
- ribbing;
- overlap;
- oscillation marks
- double wall (cover);
- discontinuously solidifying crust;
- cold junction;
- shots (splash);
- ridge;
- marks from concast product transport;
- local hot shrinkage;
- subsurface bubbles;
- pinholes.

Internal defects of concast products:
- subsurface internal cracks;
- radial cracks;
- diagonal cracks;
- cracks in the middle of the cross-section (internal cracks);
- cracks caused by transport rolls;
- centre-line porosity;
- centre-line segregation.

Shape defects of concast products:
- rhomboid-shaped deformation;
- oval-shaped deformation; swelling;
- bulging.

Surface defects
Longitudinal cracks occur when the strand surface has already lost its contact with the mould, but the strength of the outer wall of the product is lower than the tension in the solidified outer wall. The
occurrence of longitudinal cracks prevails among the external defects especially when casting low-carbon killed steel of a slab shape.

Longitudinal cracks occur due to metallurgical reasons and their formation is supported by increased temperature and casting speed which is too fast. The composition and purity of steel and proper deoxidation also have a considerable impact on the incidence of these cracks. For certain steel types, particularly when casting products of circular cross section and large slabs, the temperature of mould walls is also important. Purely mechanical cause of occurrence of longitudinal cracks is the mould misalignment in relation to the CCM’s metallurgical axis and to the direction of withdrawing of the strand. Attention should also be paid to the centring of the casting nozzle and the immersion tube in relation to the mould.

When casting different cross-sections, it is necessary to take into account that in the square cross-section of the strand, longitudinal cracks are formed on either the rounded corners or the bevelled edges, or in their immediate vicinity.

The circular cross-section is more prone to developing cracks. The relatively small surface in relation to the volume results in longer solidification of the strand. Rapidly solidified surface shell prevents shrinkage of the inner layers, leading to favourable conditions for the formation of cracks. Sometimes, already in the mould, warmer belts form on the strand at the place where a gas gap between the strand and the mould was created in contrast to much colder places at the contact surface of the strand with the mould. Direct or spiral fractures then appear at warmer areas of the strand surface with lower strength of the surface shell. Tendency to developing longitudinal tears also increases with a higher drawing speed and a higher temperature. Tear formation in circular products can be prevented, similar to other shapes, by suitably determined optimum steel temperature and optimum drawing speed, and also by modifying the mould with a suitable taper.

On slabs, as well as on square billets, tears on the edges can occur when the radius of the mould rounding is too large, while cracks in a close vicinity of the edges suggest that the radius of the rounding is too small. In such a case, a method for removing defects is preferably a choice of a proper chamfer radius and choosing a corresponding taper of the mould. Longitudinal tears along the edges of a square billet are shown in the figures.

Longitudinal tears on the edges of a square billet

Longitudinal tears in casting products near the centre and near the edges

Longitudinal tears on the slab surface which are not in the rounded or chamfered part of the cross-section and are along the longitudinal axis of the strand, can be classified as cracks near the centre and near the edges. Both types are shown in the figure. This type of tears can be caused by uneven cooling in the mould or uneven cooling of the slab in the secondary section.
Formation of longitudinal tears also depends on the casting powder quality, particularly its viscosity. If the melt viscosity of the moulding powder (or synthetic moulding slag) is low, during the mould oscillations (during the upward movement), local inlet of molten slag occurs. In these areas, concentration of tensile stress due to late development of solidified shell of the strand leads to a longitudinal tear.

Transverse tears may occur particularly due to a mismatch between the casting speed and the temperature of the mould walls. The formation of these tears depends, apart from the casting process, on the total content of carbon and sulphur in the steel. Too small bending radii for machines with horizontal outlet of strands may also lead to tears during the bending and following straightening of the strand. The occurrence of these tears is supported by various surface defects of strands, such as wrinkles, cold shuts, slag inclusions, etc., which were already created in the mould. Also, excessive contamination of steel by harmful additives such as tin, sulphur, etc. may cause tears on the surface of the strand when bending or re-straightening.

Transverse corner tears are caused by excessive bending deformation which occurs due to draw stand deviation from the metallurgical axis. Significant reduction in the incidence of transverse corner cracks can be achieved by careful adjustments and checks of drawing rolls.

Transverse facial cracks which are not in the rounded or bevelled parts of the cross section are caused by adhering to the mould or in the case of large cross-sections by abrupt cooling in the mould or in the secondary cooling system.
**Transverse depression** is a local depression of the surface perpendicular to the axis. Often occurs at regular intervals along the strand. It is caused by a lack of contact with the mould wall, which can be caused by a high cooling rate or by fluctuating levels of steel in the mould. The result is thinned shell, which can lead to transverse facial tears, bleeds or, in an extreme case, to the rupture of the shell.

The transverse depressions are also formed due to too large inflow of molten casting powder, which slows the development of solidified skin and it is then damaged by the mould moving down. Transverse depressions can be completely eliminated by a good quality and proper dosage of casting powders.

*Transverse depressions of a slab surface possibly resulting in breaking the skin*

**Bleed** is a penetration of liquid metal through a rupture in the strand skin. If the penetration of steel due to cooling effect in the mould or in the area immediately below the mould (by direct spraying) is not prevented in time, a total rupture of the casting shell occurs known as the "breakout".

**Ribbing** (also called "pocket") is a fold of slab skin caused by liquid metal flowing-around against the already solidified layer in the mould.

**Lap** occurs when the metal solidified on the surface is pushed off to the sides of the mould and gradually drawn there.

* A bleed on a slab (this part of the strand is still in the mould)  
* A bleed on a slab linked with the longitudinal tear on the edge (the corner breakthrough)  
* Ribbing (the so-called "pocket") caused by the liquid metal flowing-around against the already solidified layer  
* Lapping on the surface of a strand*
**Oscillation marks** are transverse marks located usually at distances corresponding to the track of one oscillation cycle. This phenomenon depends on the casting powder, pouring temperature and the oscillating system. The marks are therefore formed on the surface of the strand while the mould is moving up due to the disruption of the just formed upper layer.

The formation of marks, in addition to poor lubrication of the mould walls, is caused by turbulence of the liquid metal in the mould and also too low or too high temperature of the mould walls. Marks cause the occurrence of serious faults during hot forming of demanding steel grades.

![Oscillation marks in a circular cast product showing the formation of skin shrinkage](image1.png) ![Double wall on a square billet](image2.png)

**Double wall** is a clear separation of the strand surface along the whole circumference caused by the separation of the skin from the sinking cast product.

**Discontinuity of the solidifying shell** occurs only when casting insufficiently killed steel in the form of surface unevenness along the whole circumference. A change in the intensity of killing leads to the collapse of the steel surface. A skin is formed which is gradually wrapped-around during casting.

![Discontinuity of solidifying shell of a slab](image3.png) ![Cold joint in a square billet](image4.png)

Surface defects also include the "shots" i.e. oxidised steel particles trapped after splatter between the shell of the strand and the wall of the mould. Particles of previously solidified metal trapped under the surface of the strand can result e.g. from turbulent stream splatter. They can adhere to the mould plates in the upper part, this coating can fall down and be drawn into the mould. Trapped
products may remain on the surface and form bounded formations on the surface of the strand. Also particles of casting powders may be enclosed in irregular formations which are of a similar character.

Strand surface defects also include the "ridge" which results from the use of plate moulds. It is caused by the penetration of metal into the joint gaps between the plates in the corners of the cast cross-section. Marks from guiding the strand - see the picture - they can be caused by mechanical damage or imperfect shape of the supporting guide elements, bending or straightening rolls or their axial misalignment.

A **local hot shrinkage** on the surface of the strand is essentially the formation of local cracks which are usually associated with higher contents of non-ferrous metals at the grain boundaries.

**Pinholes** are small cavities similar to subsurface bubbles, located near the surface and often in larger clusters. The pinholes are usually of a 1 to 2 mm diameter, but sometimes they achieve diameters of up to 4-5 mm. They are caused by insufficient deoxidation or reoxidation during casting.

**Internal defects**
Internal defects are defect of the structure which in most cases do not penetrate onto the surface of the cast product. Therefore they are more difficult to detect. The causes of internal defects can already originate from the steel production.
For the continuous casting, phase transformations have a great influence on the occurrence of internal defects, i.e. when the liquid phase changes into the solid phase.

The occurrence of **internal tears** is caused by mechanical and thermal stress induced by phase transformations in steel. Tears are mainly formed if the critical values of tensile or compressive forces are exceeded on the boundary between the liquid and solid phases. Almost all internal cracks are formed in the range of temperatures corresponding to the "hot breaking" just below the solidus temperature. The susceptibility of steel to crack formation increases with increased content of certain alloying elements, particularly chromium, and also with high contents of other impurities, such as phosphorus, sulphur, tin, copper and antimony.

Because the stress generated at the interface between the liquid and solid phases depends on the casting speed, dimensions of the cast product and its bending radius, it is clear that it is possible to prevent the occurrence of cracks by creating the appropriate conditions for each specific case. Too high pressure of rolls on the strand can also lead to the occurrence of internal cracks. In the secondary cooling zones, cooling cracks occur when the specified intensity of the strand cooling is exceeded.

**Subsurface internal tears** are formed just below the surface of the strand. They occur 6-20 mm below the surface and their length is usually 10-30 mm. These tears are also known as the "half-way cracks". They are formed just below the mould. They may be caused either by a bulge at the bottom of the mould where the solidified skin is still thin, or they result from incorrect adjustment of the guide unit in the secondary zone.

**Star cracks** are radial cracks in the shape of a star beginning in the middle of the strand, caused by too intense secondary cooling.

**Diagonal tears** are visible cracks following the internal interface of two different planes of crystallization.
Diagonal tears in a slab strand (cross-section also shows a visible collapse)

In square strand, diagonal cracks can be extending from one corner to the other. They are caused by irregular cooling in the secondary zone and are often accompanied by oblique collapse. These cracks are caused by thermal stress caused by too intense or uneven secondary cooling.

Diagonal cracks in slab strands

Cracks in the middle of the cross-section of a slab strand

Cracks caused by drawing rolls are transverse cracks perpendicular to the roll axes, caused by reduction of the strand when the centre is still in a semisolid state. They are caused by excessive pressure of the draw rolls.

Cracks in a bloom strand caused by drawing rolls (high pressing force)

Axial centerline porosity of a square strand is shown in the figures.
Flakiness is caused by hydrogen entrapped in porosities as molecular hydrogen. This means that the precipitation of molecular hydrogen will not be reduced only by reducing the hydrogen content, but also the casting porosity.

Flakiness in a block strand

Shape defects
Defects of the regular shape of the strand are rarely a reason for rejection, but due to the changed mass of the pieces, there is more waste from further processing. For circular and square cross-sections, their further forming can be difficult.

Billet strands can deform giving rise to a rhomboid shape. This distortion increases with the speed of casting and changes along the length of the strand.

Ovality is a distortion of the circular cross-section.

Bulging is shown in the figure as a distortion of a slab of square or rectangular cross-section due to inadequate support of the skin against the effects of ferrostatic pressure.

Concavity is a distortion of a strand of square or rectangular cross-section. This defect is caused by improper method of secondary cooling.
11. Trends in continuous casting of steel:

- Outline of trends in the continuous casting machine development
  - Near net shape continuous casting
  - Casting of thin slabs with direct rolling
  - Direct strip casting:

For the continuous casting machines, the development is aimed at improving the performance and reduction of costs and energy in the use of the conventional CCMs. Steel casting with direct rolling of cast products. These technologies lead to reduced demands on a subsequent forming, reduced capital investments, operating costs and improved quality of castings. This mainly includes the casting of liquid slabs, hot strips and plates.

Near net shape continuous casting
The figure provides a diagram of this process (NNSC), the next figure shows a mould used to produce e.g. beams.

Casting of thin slabs, hot strips and plates with direct rolling
Production processes are usually classified based on the thickness of the cast products into the following categories:
- thin slabs with a thickness of 20-60 mm and a width of 1,500-2,000 mm
- strips or thin sheets with a thickness of 1-6 mm and a width of 1,200-1,500 mm
- thin strip or foil with a thickness of approx. 0.02-0.5 mm and a width of 300 mm

Continuous casting of thin slabs is further subdivided into two subgroups based on the casting speed:
1) common casting at a speed of 3-7 m.min\(^{-1}\) with the slab thickness 40-80 mm
2) high-performance casting at a speed of 15 m.min\(^{-1}\) with the slab thickness 40-60 mm.

The strips are characterized by a thickness of 2-8 mm and a casting speed of 30-60 m.min\(^{-1}\).

NNSC
- NNSC – Near Net Shape Continuous Casting

Near net shape continuous casting:
- beam blank (also the "dog bone") for the production of beams
- circular shapes of different diameters for the production of tubes and circular products - rings, wheels

The schemes below suggest the basic advantages of this machine
1) Minimising the corrections to the castings's shapes in rolling mills;
2) Increased performance of the machine;
3) Reduced costs.
As can be seen from the figure, the equipment for casting thin slabs, strips and thin strips generate additional significant energy savings due to the elimination of technological operations used in standard technologies, such as cooling of slabs and their treatment, heating, roughing. It enables the production of smaller weights of different grade steel. It will also reduce the production costs, investments and space requirements.

For these casting methods, another factor must be taken into account - the segregation phenomena. These phenomena, as mentioned earlier, are significantly related to the casting solidification rate, which affects the value of the effective distribution coefficient

\[
k = \frac{k_0}{k_0 + (1-k_0)e^{-\alpha WD}}
\]

Already specified - see Segregation
The higher the solidification rate, the higher the value of the effective partition coefficient, i.e. the lower value of the segregation coefficient. The next table provides a comparison of certain values for the casting of conventional slabs, thin slabs and strips.

<table>
<thead>
<tr>
<th>Product</th>
<th>Slab</th>
<th>Thin slab</th>
<th>Strip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness, mm</td>
<td>150 – 300</td>
<td>20 – 60</td>
<td>2 – 6</td>
</tr>
<tr>
<td>Solidification time, s</td>
<td>400</td>
<td>60</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Casting speed, m.min⁻¹</td>
<td>1 – 2.5</td>
<td>4 – 6</td>
<td>30 – 90</td>
</tr>
<tr>
<td>Heat transfer, MW.m⁻²</td>
<td>1 – 3</td>
<td>2 – 3</td>
<td>8 – 10</td>
</tr>
<tr>
<td>Weight of steel in the mould, kg</td>
<td>&gt; 5 000</td>
<td>800</td>
<td>&lt; 400</td>
</tr>
</tbody>
</table>

Due to the short solidification times for strips and thin slabs, these products have a minimum concentration differences over their cross-sections.

In the following part, just some of the possibilities and applications of these methods will be described.

**CSP, ISP methods - casting of thin slabs with direct rolling**
- CSP process with a shaped mould
- Thickness of the slab below the mould: 50 – 70 mm
- ISP process with reduced thickness below the mould
- Thickness of the slab after reduction: 15 – 25 mm

**Direct strip casting**
The main casting techniques which are used for casting thin steel strips include the systems for continuous casting with one roll, between two rotating rolls, a belt and a roll, spray casting and casting between two rotating belts.

In the systems of **continuous casting with one roll**, the tundish with melt is placed "on the roll" (side casting), where the roll "pulls" the liquid metal out of the tundish by rotary movement, or the tundish can be in a vertical position. This type of casting is rather complicated, which is mainly related to the size of the contact surface of the cooled roll and the melt. The system of casting with one roll is characterised by casting speeds ranging from 20 to 40 meters per minute and the
thickness of cast product between 0.3 and 3 mm. The main advantages of this single-roll casting system is the simple machine and variability of the strip width; the drawbacks include critical quality of the upper surface of the cast strip, the dependence of internal quality and thickness of the cast strip on the process conditions, difficult to extend the length of contact between the cast strip and the roll for a better control of solidification process, as well as a lower production range of the machine.

Diagram of the system is shown in the picture:

CCM on the principle of transporting the metal by a roll

1 - upper transport roll, 2 - supply of liquid metal, 3 - liquid steel, 4 - special tundish, 5 - solidifying metal forming a strand, 6 - lower transport roll, 7 - control sensor, 8 - output section for the cast product

Continuous casting between a belt and a roll consists in conveying the melt from the tundish through the nozzle to the "infinite" belt which is intensively cooled. A roll placed from above. The top side of the cast strip solidifies in the contact with the upper roll, while the lower side solidifies in the contact with the cooled belt which provides also the support for the strand without a large friction area. After leaving the cooling zone of the casting machine, the solidified strip travels through the travel rolls towards the forming unit. The casting speed is between 30 and 60 meters per minute and the thickness of the cast product is between 5 and 10 mm.

The advantages include a high efficiency of the machine, the fact that the cast strip is not subjected to any bending stress, the applicability of the method both for carbon steel and stainless steel, high flexibility of the casting speed and of the cast strip thickness.

The inability to change the width of the cast strip during casting, complicated control of the process and the surrounding atmosphere, and the complicated system of pouring steel on the belt belong to the main drawbacks of this method of thin strip casting.

Diagram of the system is shown in the following figure

Diagram of the rotary CCM with direct rolling
A modification of this technology is the casting of steel from the tundish onto an "endless" belt, as shown in the following figures. A tubular filling system is shown here as well as a vacuum filling system providing a constant speed and quantity of steel flowing from the tundish.

The principle of the casting between two moving steel belts is shown in the picture below.

In this casting machine, liquid steel is cast continuously from a tundish into a mould consisting of two parallel movable steel belts with a thickness from 0.5 to 0.15 mm. Between the two belts, metal blocks attached to endless belts are moving and form the side walls of the mould. Cooling and solidification of steel is achieved by continuous supply of cooling water which is fed at a high velocity onto the moving belts. To maintain the correct dimensions of the casting mould cross-section, the belts are supported from the back side by a certain number of disc rollers. The advantage of this process is the ability to achieve high performance and good surface quality.
In the **spray casting** technology, the liquid steel is sprayed onto a cooled transport drum and the thin foil is subsequently rolled - see the diagram.

1 - tank with liquid metal; 2 - spray nozzle; 3 - plug for the spray nozzle; 4 - chamber shell; 5 - thin strand; 6 - transport drum

Diagram of casting steel between two rotating cooled copper rolls is shown in the figure. This system called "CASTRIP" works in Crawfordsville (company Nucor).

Steel is produced in an electric arc furnace and is further processed in a ladle furnace. Steel flows from the ladle via a tundish into the adaptor piece leading into the nozzle. Liquid steel flows through the nozzle between two opposing rolls with a diameter of 500 mm. The usual casting speed is 80 m/min. The solidified steel strip (usually of a width of 1345 mm, which can be up to 2000 mm) is led between two supporting rolls. The strip is then routed into a rolling mill, where its thickness is reduced by approx. 40%. The resulting thickness is then within the range of 0.7 to 2.0 mm. The strip is then led to a cutter and a coiler.
Comparison
At the end of this chapter, a diagram is provided showing a comparison of a conventional continuous casting of slabs (200-300 mm), thin slabs (50-60 mm) and hot strips (0.7 to 1.8 mm). Comparison is based on:
- The design and configuration of the entire system
- Casting speed
- The difficulty and complexity of the system
- Range of rolling trains
- The length of the hall up to the strip coilers
12. References