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A Study about the Influence of Carbon Content in the Steel on the Casting Behavior

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In the casting process of steels with a C-content ranging from 0.09 to 0.53 mass%, austenite is formed as secondary crystal phase by peritectic reaction between crystal of δ ferrite and residual melt. For unalloyed or micro-alloyed steels the C-content or C-equivalent influences the casting behavior of steel in the mould, such as strand shell growth, crack formation, heat transfer, temperature fluctuation in the copper plate, mould level fluctuation and oscillation marks formation. The negative casting behavior like the uneven strand shell growth, the deep oscillation mark formation, the high mould level fluctuation, the crack formation on the strand surface were found mostly for steel with C-content or Cp between 0.10–0.13 mass%. The strand shell structure (strand shell growth, mushy zone, $\delta + \gamma$ phase transformation) and shrinkage of the strand shell were simulated depending on the C-content by means of mathematical simulation. On the basis of the simulation results and of the measured high temperature strength of steel the dependence of stiffness and the irregularity of the shrinkage of strand shell on the C-content was investigated. It was found that the stiffness and irregularity of the shrinkage of the strand shell reach the maximum value at a C-content of about 0.12 mass%.

Keywords: casting, peritectic reaction, solidification, steel, strand shell

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Introduction

Peritectic reaction in the solidification process of carbon steel is an attractive subject even though it has been investigated for a long time. The molten steel with a carbon content between 0.09 and 0.53 mass% is cooled from liquid to the peritectic temperature and the peritectic reaction, l(liquid)+ δ(ferrite) ⇒ γ (austenite), occurs during solidification. In the steel industry it is well known that peritectic steels with an equivalent carbon content between 0.1 and 0.15 mass% are the most difficult to be cast with respect to the surface quality of the continuous cast product due to longitudinal and corner cracking [1–4].

There have been a lot of investigations on why some peritectic steels are susceptible to surface crack formation on the surface of cast slab in the last thirty years. In a very early publication the influence of carbon content on the heat transfer in the mould was reported in industrial investigations. The minimum of heat flux in the mould exists for the steel with C-content of 0.10 mass% [5]. According to a theoretical calculation by Wolf and Kurz [6] the strand shell in the casting mould has the maximum stiffness and contraction for steel with a C-content of 0.10 mass%. A systematic thermal calculation shows that the highest contraction occurs for unalloyed steel with C-content = 0.10–0.12 mass% [7, 8].

In this current work a systematical study about the influence of C-content on the casting behavior will be given according to the industrial continuous casting experience, new laboratory investigations and results from the solidification simulation.

Casting Behavior in the Continuous Casting of Steel

At voestalpine the casting behaviors concerning steel strand formation, formation of oscillation marks, mould level fluctuation and heat transfer in the mould have been investigated depending on the equivalent carbon content regarding the peritectic reaction. The casting conditions for the investigation were as follows: The casting speeds amounted to 1.2–1.4 m/min, the super heating was 20–30 °C, slab sizes were (215-210) × (1200-1500) mm. The mould was sinus oscillated. The stroke heights amounted 6-8 mm, oscillation frequency 110–120/min. The mould level is controlled by the Co60.

Strand Shell Growth. The formation of the strand shell is dependent on the steel analysis. It was found that the growth of strand shell was uneven for steels with C = 0.1 mass% [9, 10]. **Figure 1** shows the strand shells from the break-out heats of steels with different Carbon equivalent Cp. **Figure 1a** shows strand shell for steel with Cp = 0.04, **Figure 1b** shows strand shell for steel 0.10 and **Figure 1c** shows strand shell 0.25 mass%. Carbon equivalent Cp was calculated using a formula from literature [11]. The grey zone shows the thickness of strand shell from mould level (at the top) to the mould exit. **Figure 1d** shows the outer surface of strand shell and **Figure 1e** shows the interior surface of strand shell. For steel grades with Cp = 0.04 and 0.25 mass%, a uniform strand shell in the mould is formed and with Cp = 0.10 mass% a non-uniform strand shell is formed. It is noteworthy that on the outside of the strand shell (slab surface) depressions and on the inside of the strand shell a

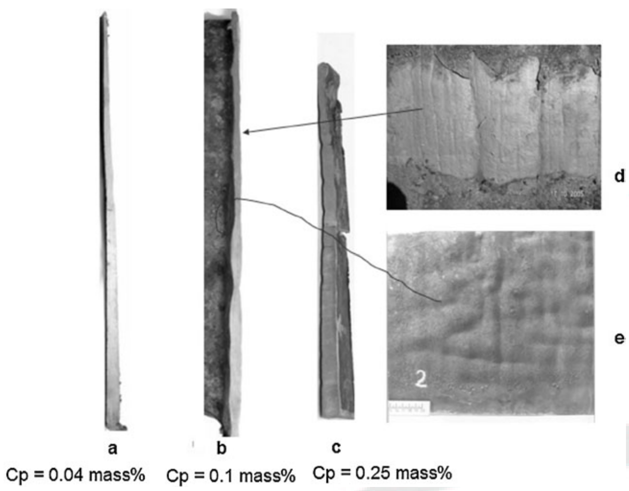

Figure 1. Strand shells from break-outs heats of different steels.

wavelike surface are observed for steel grades with Cp = 0.10 mass%.

Oscillation Marks. The influence of carbon on the oscillation mark formation was investigated in the literature [12–14]. They found that the cast slabs of steel with C = 0.1–0.12 mass% have deeper oscillation marks. In present paper the 6 steel slab samples with Cp = 0.002, 0.05, 0.08, 0.10, 0.135 and 0.18 mass% were taken from the continuous casting slabs which were cast under similar casting conditions: casting speed = 1.2 m/min, stroke height = 6–8 mm, oscillation frequency = 110–120/min and superheating = 20–30 °C. The oscillation mark depths were measured. For steel grades with Cp = 0.08–0.135 mass% the oscillation mark depths are higher than for steels with Cp = 0.002, 0.05 and 0.18 mass% (**Figure 2**). The metallographic investigations were made for steel grades with Cp = 0.135 and 0.21 mass% (see **Figure 3**). This shows that the oscillation marks for steel grade with Cp = 0.135 mass% are deeper than that for steels with Cp = 0.22 mass%. On the bottom of the oscillation marks for steel with Cp = 0.135 mass% the cracking is found.

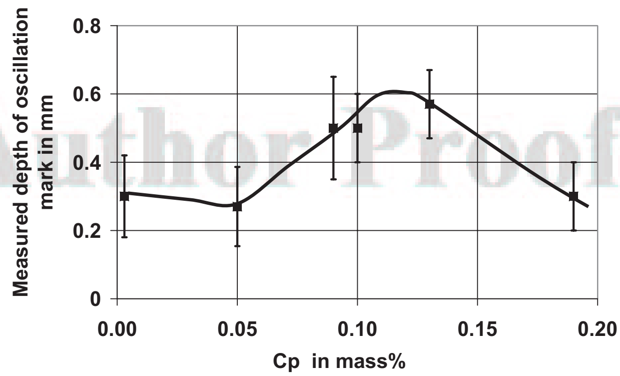

Figure 2. Influence of carbon equivalent (Cp) on the depth of oscillation marks.

Mould Level Fluctuation. In a work by Lamant [15] it was found that the mould level fluctuation for casting of steel with C = 0,09–0.12 mass% is higher than that for casting of steel with C < 0.07 mass%. A statistical evaluation of the mould level fluctuation relating to steels with different Cp has been conducted. In this investigation six steel grades with Cp 0.05, 0.07, 0.10, 0.11, 0.14 and 0.22 mass% are concerned. The mould level is controlled by the Co60. The slab sizes were 220 × (1300–1500) mm, the cast speed was 1.2 m/min and superheating was 20–30 °C. The mould level variation coefficient is used as an index to characterize the mould level fluctuation. It is calculated by the division of standard deviation of mould level by the mean value of the mould level. The investigation shows a definite dependence of mould level fluctuation on the Cp. The steel grade with Cp = 0.11 mass% has the highest mould level fluctuation, see **Figure 4**.

Mould Thermal Behavior. The influence of carbon content on the thermal behavior of mould has been mostly reported. For casting of steels with C = 0.09–0.12 mass% there were higher temperature fluctuation in the mould copper plate and lower heat flux in the mould [5, 10, 11, 16–25]. The present investigation of the influence of carbon equivalent on the mould thermal behavior (heat transfer and

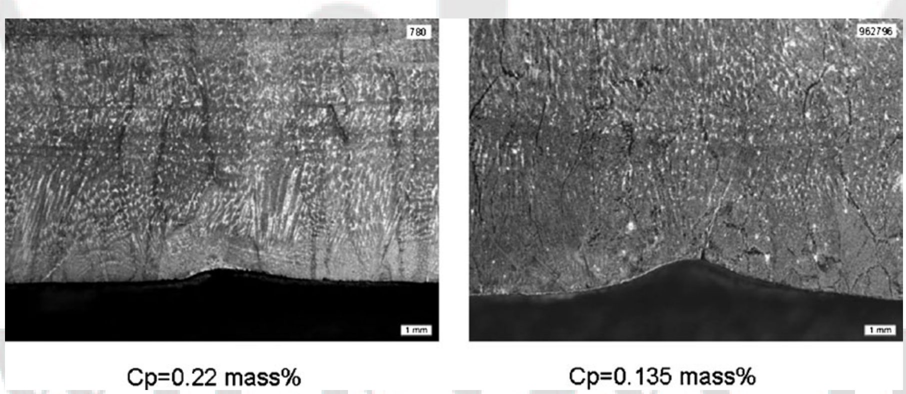

Figure 3. Metallographic pictures of the oscillation marks.

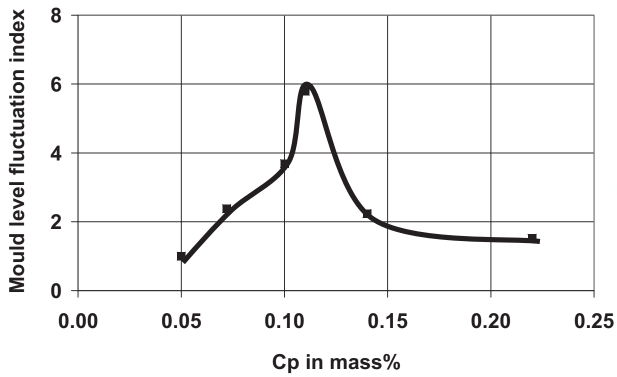

Figure 4. Influence of Carbon Equivalent Cp on the mold level fluctuation under comparable Casting Conditions.

temperature variation in the copper plate) shows there is a minimum of heat flux in the mould and a maximum of copper plate temperature variation coefficients for steel with Cp = 0.12 mass%. The investigation has been carried out for the same casting conditions: The casting speeds amounted to 1.2 m/min, the super heating was 20–30 °C, slab sizes were (215-210) × (1200-1500) mm. The mould was sinus oscillated. The stroke height amounted 6–8 mm, oscillation frequency 110–120/min. **Figure 5** displays the dependence of heat flux and temperature variation on the carbon equivalent.

Simulation of the Solidification Process in the Mould

At voestalpine a mathematical model [26] was developed by combining thermal, segregation, phase transformation and shrinkage models in order to investigate the behavior of the steel strand shell. The outputs of the model are the structure of strand shell, temperature profile, shrinkage and stiffness of strand shell.

Strand Shell Solidification Structure in Meniscus Area. The solid fractions $f_S = 0.8$ and 1 are termed here as zero strength solid fraction (ZSF) and zero ductility solid fraction (ZDF) respectively. A steel shell with a zero strength, zero ductility and $\delta + \gamma$ phase transformation at the strand surface is formed at a distance from the mould level. This distance will be called as "mould level distance". The area between the solid fractions $f_S = 0.8$ and 1 is called the brittleness area. A larger distance in the casting direction at the strand surface between $f_S = 0.8$ and 1 and between the beginning and end of $\delta + \gamma$ phase transformation means a thicker strand shell concerning brittleness area and $\delta + \gamma$ phase transformation area. It is interesting to know about the influence of carbon content on the "mould level distance", strand thickness at the time of the occurring of $\delta + \gamma$ phase transformation.

Figure 6 shows the simulated strand structure (strand thickness) for the solid fractions $f_S = 0$, 0.8, 1 and $\delta + \gamma$ phase transformation in the mould within a distance of 0–100 mm from the steel mould level. The selected steel analyses are with carbon contents of 0.05, 0.10, 0.12 and 0.18 mass%. The contents of Si, Mn, P, S,. . ..are set to zero. The casting conditions are the same for the simulation: the casting speed 1.2 m/min, superheat 25 °C and heat flux in the mould 1.2 MW/m^2.

For steel grade with a C-content of 0.05 mass%, the brittleness zone $f_S = 0.8$–1 is located in the δ + liquid phase (**Figure 6a**). The thickness of the brittleness zone amounts to 0.13 mm at 50 mm distance to the mould level. The $\delta + \gamma$ phase transformation occurs in the ductility area and begins in 1.6 mm strand thickness in terms of $f_S = 0.8$ (ZSF) and 44 mm below mould level. The thickness of $\delta + \gamma$ phase transformation area amounts to 0.17 mm at a 50 mm distance to the mould level.

For steel grade with a C-content of 0.10 mass%, the brittleness zone $f_S = 0.8$–1 is located in the δ + liquid phase (**Figure 6b**). The thickness of the brittleness zone amounts to 0.28 mm at a 50 mm distance to the mould level. The $\delta + \gamma$ phase transformation occurs near brittleness area and begins at 0.3 mm strand thickness for $f_S = 0.8$ (ZSF) and 15 mm below the mould level. The thickness of $\delta + \gamma$ phase transformation area amounts to 0.45 mm at a 50 mm distance to the mould level.

For steel grade with a C-content of 0.12 mass%, the brittleness zone $f_S = 0.8$-1 is located partly in the δ-liquid phase and partly in the $\delta + \gamma$ + liquid phase (**Figure 6c**). The thickness of the brittleness zone amounts to 0.28 mm at a 50 mm distance to the mould level. The $\delta + \gamma$ phase

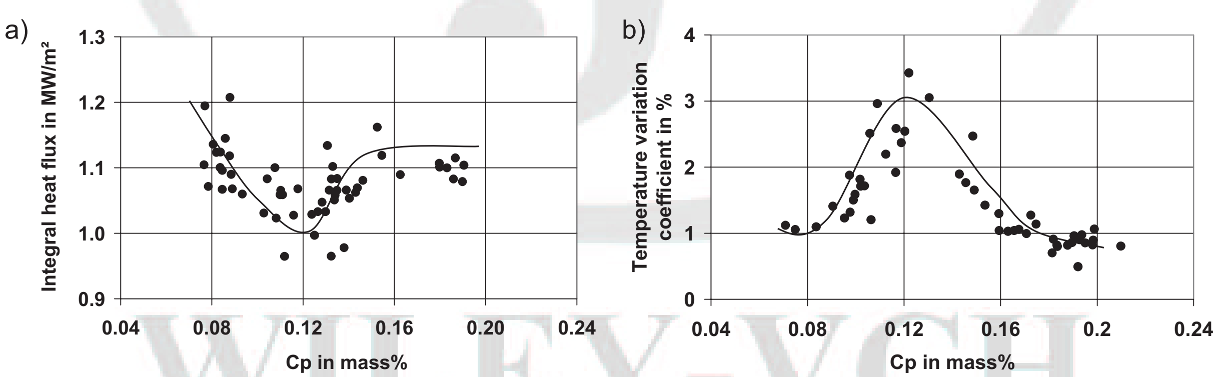

Figure 5. Influence of Cp a) on the integral heat flux, b) on the temperature variation coefficient in the mould (casting speed vg = 1.2 m/min)

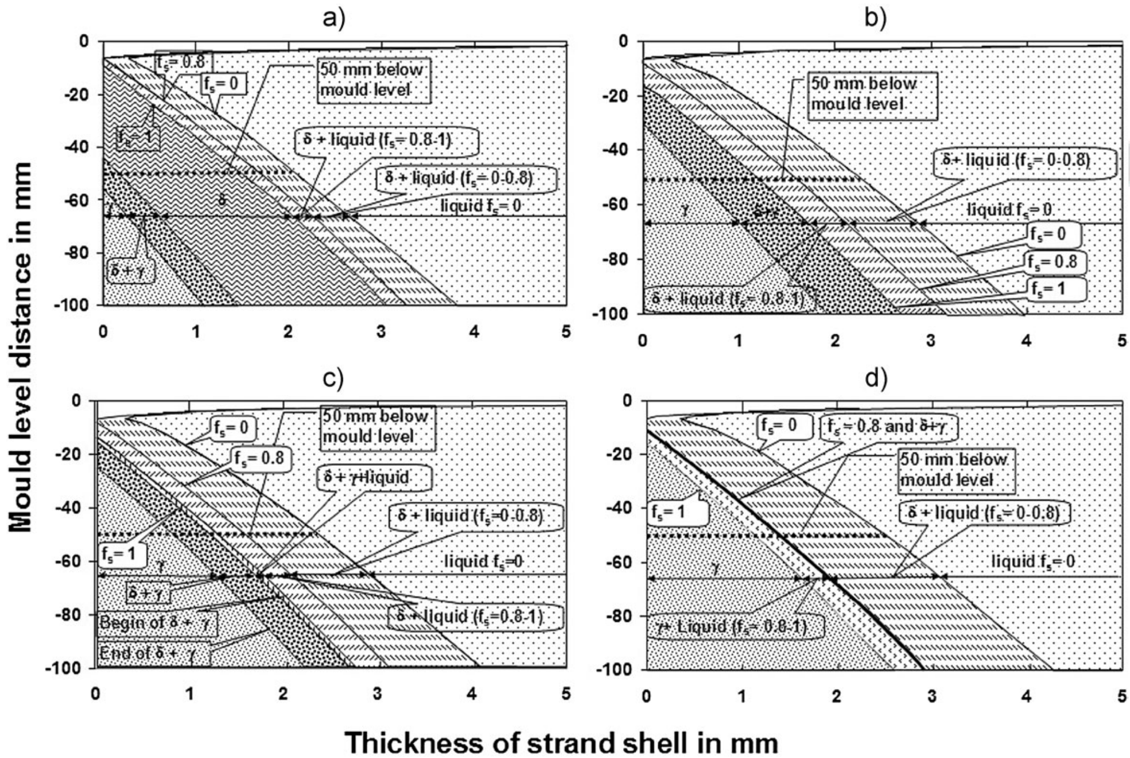

Figure 6. Solidification structure in the meniscus region of the mould: a) C = 0.05, b) C = 0.10, c) C = 0.12, d) C = 0.18 mass%.

transformation occurs in the brittleness zone partly and begins at 0.22 mm strand thickness in terms of $f_S = 0.8$ (ZSF) and 14 mm below the mould level. The thickness of δ + γ phase transformation area amounts to 0.33 mm at a 50 mm distance to the mould level.

For steel grade with a C-content of 0.18 mass%, the brittleness zone $f_S = 0.8\text{-}1$ is located in the γ + liquid phase (**Figure 6d**). The thickness of the brittleness zone amounts to 0.2 mm at a 50 mm distance to the mould level. The δ + γ phase transformation begins at 0.0 mm strand thickness in terms of $f_S = 0.8$ (ZSF), and occurs in a very small area like a thin band in the strand and 11 mm below the mould level.

The strand structure in the meniscus area concerning solidification on the strand surface is simulated. The carbon contents for the steel amount to from 0 to 0.40 mass% and the contents of Si, Mn, P, S,. . ..amount to 0 mass%. The casting conditions are the same for the simulation: the casting speed 1.2 m/min, superheat 25 °C and heat flux in the mould 1.2 MW/m^2. In **Figure 7** the correlations between the mould level distance and the C-contents is shown. For example, with a steel with a C-content 0.10 mass%, the strand shell referring to $f_S = 0.8$ is formed at an approximate 9 mm distance to mould level. The δ + γ phase transformation begins at about 15 mm distance to the mould level and ends at about 37 mm distance to the mould level.

In Figure 6 and 7 the influence of C-content on steel solidification behavior is summarized as follows:

- The strand thickness referring to $f_S = 0.8$ at the beginning of the δ + γ phase transformation decreases with higher C-content.
- The thickness of δ + γ phase transformation area has the maximum for steel with C-content of 0.1 mass%.
- The δ + γ phase transformation occurs earlier with higher C-content, and takes place for C < 0.1 mass% in the completely solidified area ($f_S = 1$).
- For steel with a C-content = 0.11–0.18 mass% the δ + γ phase transformation occurs in the δ + γ+ liquid phase.

Shrinkage of Strand Shell. The calculation for a free shrinkage strain on the strand surface in the mould without taking external or internal stress into consideration was made for different steel grades with C = 0.05, 0.10, 0.12 and 0.18

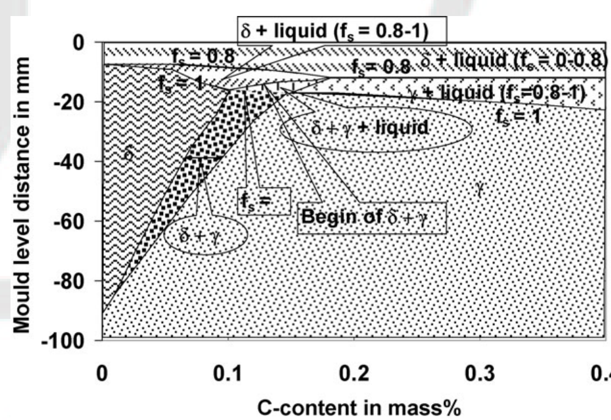

Figure 7. Solidification of steel in the mould on the strand surface depending on C-content.

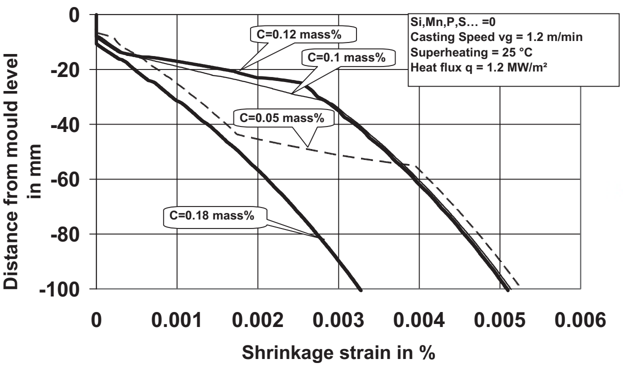

Figure 8. Calculated shrinkage strain as a function of the distance from the mould level.

mass% at a casting speed of 1.2 m/min (**Figure 8**) [26]. The vertical axis represents the distance from the mould level and the horizontal axis describes the shrinkage strain on the strand surface. In Figure 8 it is seen that irregular shrinkage takes place stepwise at steel grades with C = 0.05, 0.10 and 0.12 mass%, and regular shrinkage at C = 0.18 mass%. In the case of irregular shrinkage the step with decreasing C-content is located far away from the mould level.

In order to describe the irregular shrinkage of strand shell a index of irregular shrinkage is calculated using following formula:

$$\begin{aligned}&\text{Index of irregular shrinkage}\\&\quad=\text{shrinkage strain variation coefficient} * \text{thickness of } \delta\\&\quad+\gamma \text{ phase transformation area at 50 mm distance from}\\&\qquad\text{the mould level}\end{aligned}$$

The variation coefficient of shrinkage strain is obtained by dividing the standard deviation by the mean value of shrinkage strain within the range from mould level to 50 mm below mould level. **Figure 9** shows the dependence of irregular shrinkage of strand shell on the C-content. In the range of C = 0.05–0.18 mass% there is the maximum of irregular shrinkage for C-content of about 0.11 mass%.

Stiffness of Strand Shell. The resistance against deformation of the strand shell is defined as the "stiffness" of the steel strand shell in the present work. This "stiffness" is influenced by the steel strength and the shell thickness related to ZSF (solid fraction $f_S = 0.8$). The strength of steel depends on the temperature and on the phase structure of the strand shell. If the stiffness of the strand shell gets lower during or after $\delta + \gamma$ phase transformation then the gap between the strand shell and the mould wall caused by irregular shrinkage can be reduced easily by ferrostatic pressure against the mould wall. But if the stiffness of the strand shell gets higher during or after the $\delta + \gamma$ phase transformation then the gap between the strand shell and the mould wall caused by irregular shrinkage cannot be easily reduced by ferrostatic pressure against the mould wall.

Muzukami [27] has measured the tensile strength of the steel grades with different C-contents C = 0.005, 0.04, 0.08, 0.10, 0.14, 0.18 0.28 and 0.56 mass% at different temperature of samples. The maximal stress was defined as tensile strength of samples which were pulled at a strain rate of $1 \times 10^{-2}\,s^{-1}$. The contents of other steel composition are very low. The measured tensile strength values are applied to calculate the strand stiffness. A simple formula is used to calculate stiffness index of strand shell at a 50 mm distance from the mould level:

$$\text{Stiffness index} = \sum \sigma_i\, d_i$$

σ_i is measured tensile strength of δ phase, γ phase, $\delta + \gamma$ phase, δ + liquid, γ + liquid at a strain rate of $1 \times 10^{-2}\,s^{-1}$ and at the different temperature. d_i is strand thickness of δ phase, γ phase, $\delta + \gamma$ phase, δ + liquid, γ + liquid at a 50 mm distance from the mould level. They can be calculated with the solidification model.

The stiffness index of the strand shell at a 50 mm distance from the mould level is calculated using the simulated solidification structure of strand shell and the tensile strength of steel at high temperature measured by Muzukami. The casting conditions and heat transfer in the mould are the same for all steels. In **Figure 10** the dependence of stiffness index on the C-content is shown. For steel grades with a C-content < 0.05 mass%, the stiffness index of the strand

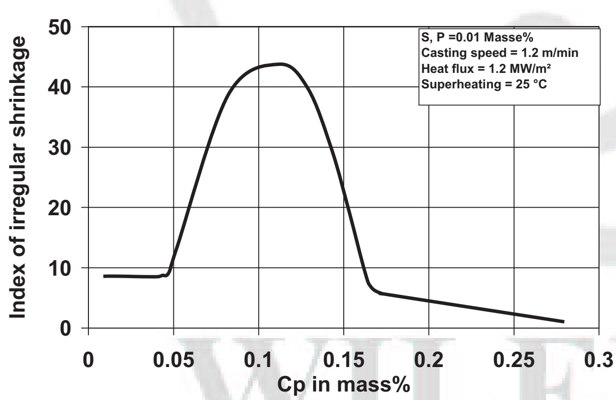

Figure 9. Calculated index for irregular shrinkage as a function of Cp.

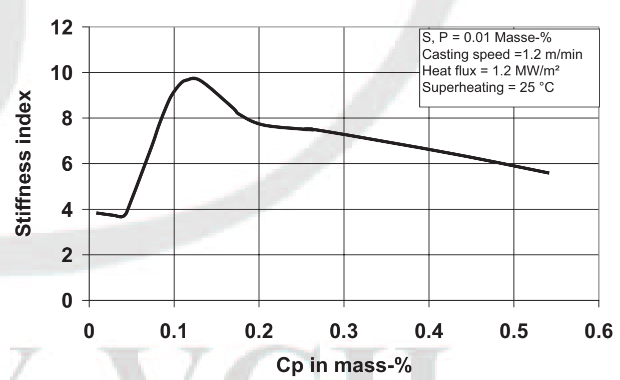

Figure 10. Calculated index for strand shell stiffness as function of Cp.

shell is not changed, because the strand shell consists of the δ phase from mould level to 50 mm distance below meniscus. The stiffness index of the strand shell for steel grades with a C-content > 0.05 mass% has the maximum for steels with C-content von 0.12 mass%. The reason for this maximum is an increasing γ phase fraction in the strand shell for steels with C-content from 0.05 to 0.12 mass% and a decreasing solid phase fraction in the strand shell for steels with C-content > 0.12 mass%.

Discussion

The knowledge about solidification and mechanical behavior of the strand shell in the meniscus area supplies an important basis for understanding the casting behaviors like strand shell growth, oscillation marks formation, mould level fluctuation and thermal behavior which depend on the carbon equivalent Cp.

The growth of the strand shell is influenced by two factors: mould slag film between the strand shell and mould, and solidification of liquid steel. If the slag film has non-uniform properties or non-uniform thickness, the strand shell should grow uneven. For the non-alloyed steel there are no findings about that. The solidification should be the main factor which influences the strand shell growth. The finding that there is the maximum of non-uniform shrinkage and stiffness of strand shell for steel with Cp = 0.12 mass% may give a reasonable explanation why the strand shell for steel grades with Cp = 0.1–0.13 mass% grows most unevenly.

The oscillation marks are caused mainly by mould oscillation and influenced by oscillation parameters. The investigation confirms that the crack formation on the strand surface occurs mostly on the bottom of marks, see Figure 3. Thermal mechanical calculation shows that the strain on the bottom of marks is many times larger than between oscillation marks [28]. The strand with severe marks is susceptible to cracking. The oscillation marks are not only influenced by the mould oscillation, but by the steel analysis [12–14]. In the case of the high strength and thicker strand shell more severe oscillation marks are formed. The maximum of "stiffness" for the steel grades with Cp = 0.12 mass% may explain the reason why the oscillation marks are the deepest for Cp = 0.10–0.13 mass%.

The mechanism about the influence of Cp on the mould level fluctuation is complicated. In Figure 1 it is seen that the strand shell grows unevenly not only on the mould side but also in the liquid steel side for steel grades with Cp = 0.10 mass%. In **Figure 11** a uniform and a non-uniform strand formation are demonstratively showed. Figure 11a shows uniform and 11b non-uniform shell formation. The strand shell is withdrawn continuously. For the uniform strand shell the internal sections area of strand at a certain distance from mould level is constant, whilst the internal sections area of strand is non-uniformly changed for the non-uniform strand shell. This non-uniform changing of the internal cross section may be one reason for the higher mould level fluctuation.

The mould thermal behavior in dependence on the Cp must be influenced by the strand shell growth, the oscillation

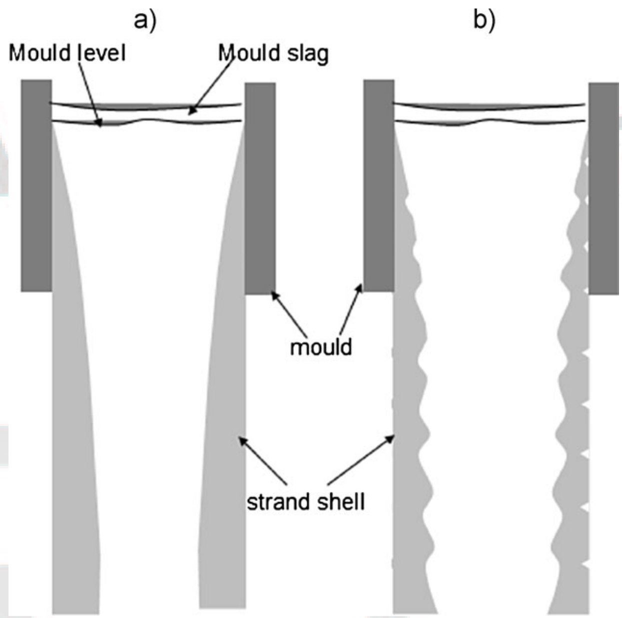

Figure 11. Demonstrative picture for a uniform (a) and a non-uniform (b) formation of strand shell

marks formation and mould level. In the case of uniform strand shell, weak marks formation and a stable mould level the temperature in the mould plate has a little fluctuation. In the case of the non-uniform strand shell growth and strong mark formation there is bad contact between the strand shell and mould. The lowest heat flux at Cp = 0.12 mass% is caused by non-uniform strand shell growth and strong mark formation.

In order to obtain a favorable casting behavior, the non-uniform shrinkage and stiffness should be decreased. Having a steel analysis avoiding Cp = 0.12 mass% is an effective method to lower non-uniform shrinkage and stiffness.

In a simulation of the influence of heat transfer in the mould on the non-uniform shrinkage and stiffness of strand shell it is found the non-uniform shrinkage and stiffness of strand shell depend on the heat flux. In **Figure 12** it is to be

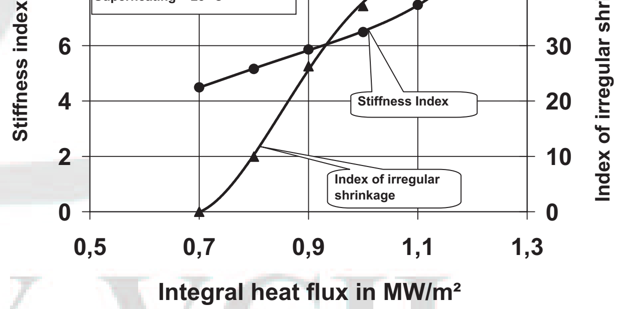

Figure 12. Influence of heat flux in the mould on the stiffness of strand shell and the non-uniform shrinkage.

seen that the lower the heat flux, the lower the non-uniform shrinkage and stiffness. This finding shows that decreasing the heat flux in meniscus area can improve casting behavior for crack-sensitive steel.

Conclusion

From continuous casting operation practice we see the dependence of casting behavior like strand shell growth, oscillation marks formation, mould level fluctuation, mould thermal behavior and cracking formation on the carbon equivalent Cp. The steel grades with Cp = 0.10–0.13 mass% have the worst casting behavior. The solidification simulation combined with the measurement of steel strength at high temperature shows that there is the maximum of non-uniform shrinkage and stiffness for steel grades with Cp = 0.10–0.13 mass%. This high stiffness and non-uniform shrinkage are main reasons for the most non-uniform growth of strand shell.

For steel grades with Cp = 0.10–0.13 mass%, the oscillation marks are deeper due to the higher stiffness of the strand shell, the mould level fluctuates strongly due to non-uniform strand shell growth, the heat flux at a minimum is in the mold due to the non-uniform strand shell growth, the temperature in the copper plate of the mould fluctuates strongly due to the non-uniform strand shell growth and strong oscillation mark formation. The crack formation on the strand surface is caused by the superposed effect of deeper oscillation marks, strong mould level fluctuation and non-uniform shrinkage in brittleness zone ($f_S = 0.8 - 1.0$).

The following measures are necessary in order to decrease the cracking on steel slab:

- With a suitable casting powder or solidification control in the meniscus area the heat flux in the meniscus area will be decreased.
- The mould tapering should be improved, like parabolic profile of mould plate.
- The mould oscillation should be optimized.
- The mould level control system should be improved for lowering the mould level fluctuation.
- The crack-sensitive steel analysis should be avoided.

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