Further Results from Strip Casting with the Single-Belt Process

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The integrated single-belt casting/hot rolling process operated at Clausthal Technical University is described with emphasis on the machine operation. Automatic control of the relevant parameters is very important in strip casting with high linear velocities involving the additional process steps of hot rolling and coiling. The following quantities are measured, controlled and/or stored as process data by a computer system: (a) the temperatures of the liquid steel in the furnace/ladle and in the dispenser and of the strand at the entrance to the rolls, (b) the flow rate of the liquid steel discharged from the ladle into the dispenser, (c) the velocities of the belt, of the strand and of the rolled strip, (d) the roll gap, (e) the lateral position of the belt, and (f) the oxygen content of the gas in the strand encasing. The various controls are described and examples of the time records of the controlled quantities are given. The second part of the paper deals with the feeding system. At present two argon rakes made up from a row of little argon jets are used to enhance the lateral distribution of the melt on the belt. In the third part of the paper the materials properties of the product are discussed. It is shown that the internal porosity can be removed securely by hot rolling with a reduction degree of about one. Some results are given on the inclusion distribution in the as-cast material.

KEY WORDS: near net shape casting; single-belt process; strip casting with in-line hot rolling.

1. Introduction

Clausthal Technical University has been engaged for many years in developing a near net shape casting process for making steel strip.1–7) At present we are operating a single-belt caster of pilot size with an in-line rolling facility. The work is carried out in cooperation with Salzgitter AG, with Mannesmann-Demag AG Metallurgy and with Thyssen-Krupp Stahl AG. There is a parallel project on the process conducted by MEFOS in Sweden.4,7) Both projects are partially financed by the ECSC and are closely coordinated. Most of the research has been performed up to now on the castability of mass steel grades (carbon steels).

The pilot plant operated in Clausthal is described in Fig. 1. A photograph is shown in Fig. 2. The geometrical data are given in the tables inserted in Fig. 1. In the single-belt process the steel melt is fed from the dispenser onto a moving belt cooled from below by water jets emerging from nozzles. After leaving the caster the strand is transported on a roller table to the rolling mill which is a duo in Clausthal, and after rolling the strip is coiled. In thin casting it is necessary to minimize oxidation by air. Therefore, the casting machine and the roller table are encapsulated to enable casting under a protective atmosphere of argon. The mass of steel available in Clausthal is 500 kg at present but will be 1.3 t in the near future. The steel is melted in an induc-

Fig. 1. Sketch of pilot installation for the integrated single-belt casting/hot rolling process at Clausthal Technical University.
tion furnace which serves also as the ladle. There is a bottom tap hole in the furnace with a stopper rod.

The new process is particularly well suited for the production of mass steel grades (carbon steels) yielding the following benefits:

- There is no problem due to machine geometry as with the twin-roll caster, to reach high productivities. Since the “mold” travels horizontally (in the form of the belt) the increase of productivity only requires an increase of the length of the cooling belt. That is high speed casting is possible without difficulty from this geometrical point of view.
- At present most metallurgists in the field believe that carbon steels cannot be directly cast with hot strip thickness. Instead, hot rolling with a thickness reduction of 60 to 80% is necessary to achieve securely the closure of all pores and good technological properties. This means that the strand has to have a thickness in the range of 10 to 15 mm which, after in-line hot rolling, can yield a strip of 2 to 4 mm. The single-belt process was designed for casting in this thickness range so that the necessary amount of hot rolling is still possible.

2. Process Control

It has been realized already at an early stage that the strip casting with high linear velocities involving the coupled additional process steps of hot rolling and coiling can be performed only with an automatic control of the relevant operation parameters. For instance, the flow rate of the liquid steel onto the belt, the speed of the belt, the rolling speed and the speed of the coiler have to be adjusted to each other. The process control system applied is explained in Fig. 3. The control is carried out by a computer operating a real time system. The process steps during start up are scheduled by the process control computer and the overall process synchronization is performed. The set points for the subprocesses (e.g. flow rate of steel) are calculated and transferred to the programmable logical controllers (PLC) which control the subprocesses. Furthermore, the process control computer is in charge of process data acquisition and of post-process data analysis.

2.1. Temperature Control

The temperature of the steel in the dispenser, particularly also the superheat, is a parameter of significant influence on the uniformity of strand cross section and on the surface quality and, therefore, has to be controlled carefully. For this purpose a thermocouple protected by an alumina graphite tube is inserted into the melt contained in the crucible of the furnace. This is a commercial system which is designed for temperature measurement in the tundish of conventional continuous casting machines. It allows a permanent temperature control over several hours. Based on this temperature measurement a PLC controls the power input to the induction furnace to bring the temperature to the set point and then keep it there.

Other temperatures which are not used for automatic controls is a temperature in the dispenser and a strand tem-
perature. The first temperature is measured with a thermocouple protected by a silica tube and placed in the duct of the dispenser about halfway between the steel inlet and the nozzle exit. This temperature is used to check proper preheating of the dispenser and the course of the temperature during casting. The surface temperature of the strand is determined with a pyrometer at a location close to the entrance of the rolls. Both temperatures are stored as process data.

Figure 4 shows the three temperatures during an experiment. The melt temperature in the furnace is kept at 1 570°C which is a typical value corresponding to about 50°C superheat for the ST 37 steel grade cast (0.13% C). During casting the temperature in the furnace first stays on the set value and then drops somewhat when the steel level sinks below the position of the thermocouple.

The temperature in the dispenser (gas temperature) during preheating is about 930°C. When the dispenser is moved into casting position preheating is stopped and the temperature drops to about 700°C. Then the charging of the steel starts. The temperature increases strongly, then levels off when the steel reaches the thermocouple because some steel freezes at the sheath initially, and then approaches to the steel temperature in the furnace. When the furnace is empty the level of steel decreases in the dispenser and so does the temperature.

The temperature at the upper surface of the strand before the rolling stand is between about 1 200 and about 1 250°C. This is too high compared to normal hot rolling of steel. Lower rolling temperatures could be achieved with a longer roller table which, however, can not be realized at the present location of the pilot plant in Clausthal.

2.2. Control of Steel Flow Rate

The flow rate of the steel from the furnace into the dispenser is regulated by controlled upward motion of the stopper rod. As the drainage of the furnace is a transient phenomenon it can be hardly controlled by a simple algorithm. Therefore, the following semi-physical approach based on Bernoulli’s equation is used. The real mass flow rate \( q \) is taken to be according to equation

\[
q = bs \sqrt{w - w_0} \quad \text{(1)}
\]

where \( s \) is the lift of the stopper rod above its position at closure of the tap hole, \( w \) the weight of the furnace, \( w_0 \) the weight of the empty furnace, and \( b \) a coefficient. The weight is measured via load cell installed in the suspension to the crane carrying the furnace. The set point for the lift to achieve the desired mass flow rate \( q_{\text{aim}} \) is calculated by the process computer and controlled by the corresponding PLC via expression

\[
s = \alpha \frac{q_{\text{aim}}}{b \sqrt{w - w_0}} \quad \text{(2)}
\]

The correction factor \( \alpha \) is determined (PI control algorithm) according to the formula

\[
\alpha = 1 + c \int_0^t \Delta q dt + e \Delta q \quad \text{(3)}
\]

where \( \Delta q \) is the difference between the required and actual mass flow rates, \( \Delta q = q_{\text{aim}} - q_{\text{actual}} \), and \( c \) and \( e \) are constants which have to be adjusted. The zero of time \( t \) is when the control starts. The actual flow rate is determined from the signal of the load cell.

An example for the traces of the various quantities is given in Figure 5. Figure 5a shows the stopper rod position \( s \) (lift) and Fig. 5b the correction factor \( \alpha \), as a function of time. The zero of time is when the vacuum pumps are switched on to produce the low pressure below the belt. Figure 5c gives the measured weight of the charge in the furnace. The apparent variation of the weight before starting the stopper lift is due to the crane movement and to the setting of the set point. Figure 5d shows the desired and actual mass flow rates \( q_{\text{aim}} \) and \( q_{\text{actual}} \). Initially the dispenser is filled with a high mass flow rate, then \( q_{\text{aim}} \) is reduced for a few seconds in order to avoid splashing when the steel enters onto the belt. When the belt has started to move \( q_{\text{aim}} \) is set to its final value.
Fig. 6. Velocities of belt, strand and strip as a function of time in a typical experiment.

Fig. 10. Effect of clogged feeding holes during feeding with the zig-zag nozzle, a) photograph showing non-uniform feeding from nozzle, b) resulting feeding marks at the lower strand surface.

Fig. 16. Local distribution, size and type of oxide inclusion.
Synchronization of the speeds of belt, strand and hot rolled strip is essential for proper casting with in-line rolling. Tachometers are used to measure the speed of the strand before rolling and of the strip after rolling. The belt movement begins when the liquid steel impinges on an electric contact at the dummy bar. After the short time of start up the belt speed is kept constant. The set point for the belt speed is chosen, in accordance with the set point for the mass flow rate, to yield the desired strand thickness. Before the strand has reached the rolling stand the strand speed is made by the dummy bar drive. When the strand has entered into the roll gap the rolls are closed, triggered by an infrared sensor. Afterwards the strand speed is determined by the angular velocity of the rolls. This velocity is chosen to yield a strand speed equal to the belt speed, or slightly less to account for shrinkage of the strand. The speed of the coiler is set about 3% higher than the speed of the strip at the roll exit. But the coiler torque is limited to avoid slip between coiler and strip so that effectively coiler and strip speeds are equal. This is the same as in hot rolling mills.

Figure 6 shows a record of the speeds of belt, strand and strip. During the initial phase all the three velocities are approximately equal. The speeds denoted as those of the strand and strip are those of the pulling cold strand (dummy bar). At about 160 s the roll gap is closed and, consequently, the strip speed behind the rolling stand goes up. As can be seen, apart from a short time at the beginning of rolling, the strand speed is very close to the belt speed, that is there was negligible slip between strand and belt in this experiment. At the end of the cast which is at about 220 s, the furnace is almost empty. Due to the decreased mass flow rate the thickness of the strand becomes smaller than the roll gap. Consequently, the speeds before and behind the rolls become the same again and equal to the coiler speed. As the coiler is set to move slightly faster than the strip a speed up of the strand takes place.

2.4. Roll Gap Control

The size of roll gap is measured by transducers and is adjusted hydraulically, in a conventional manner, to the set point, after prepositioning by the spindles. The locations of spindles, hydraulic cylinders and transducers are depicted in the upper part of Fig. 7. The lower part of Fig. 7 shows a record of the gap size during an experiment. The rolls are closed at about 160 s. The control system activates both hydraulic pistons, but first moves that at the drive side to the set point. The value reached at this side is then used as the set point for the non-drive side. This means that the control system aims at keeping a parallel roll gap even if the set point is not reached at the drive side. The alternative control strategy to reach the set point at both sides simultaneously gave a poorer performance with respect to transverse thickness uniformity of the strand. As can be seen in Fig. 7 the set point of 10 mm is not perfectly attained. Also, there is an oscillation with an amplitude of about 100 μm with the wavelength corresponding to the circumference of the rolls. Presumably, this oscillation is triggered by forces exerted by the drive shafts. There is also a certain difference between the gap size at both sides which is again in the order of 100 μm.

Although the rolling duo does not work perfectly (it is very old and was received as a gift) it performs completely satisfactorily to prove that coupled casting and hot rolling is feasible which is one of the objectives of the Clausthal research work.

2.5. Control of Lateral Position of the Belt

Due to geometrical tolerances both of the casting machine and of the belt, the belt tends to move in lateral direction to the one side or to the other. Therefore, a control system is needed to keep the belt in position. For this purpose, at the Clausthal caster, the tension roll is used which can be tilted by two pressurized air pistons, Fig. 8. The belt edge position is measured optically. Based on this measurement the two pistons are activated using a PLC. In Figs. 8a and 8b the records of the edge position and of the pressures in the cylinder are given for a period of several belt revolutions. The peaks and subsequent drops of the edge position result from a lateral dislocation of the two ends of the steel sheet at their welding line, from which the belt is made. Sufficient care must be exerted in the welding procedure to avoid imperfect fit of the ends at the welding line. The record of belt position of a perfectly welded belt is depicted in Fig. 8c.

2.6. Measurement of Oxygen Content

As has been mentioned in the introduction the strand is kept in a protective atmosphere from the feeding point to the hot rolling stand. The argon is added at three inlets located on the cover lid of the encasing. The controlled flow rates are achieved via valves operated in a duty cycle mode. The oxygen content is measured at three locations. Figure 9 shows the oxygen content at the middle location which is halfway between caster exit and rolling stand. Before the start of the experiment the oxygen content is brought down to below 1%, e.g. 0.5%. When the hot strand reaches the measuring position the remaining oxygen is removed very
fast by reaction with the steel and the atmosphere is nearly free of oxygen. In a production unit the nitrogen content would be monitored which is a measure of leakage, and the argon addition would be metered according to an upper limit set for the nitrogen content.

3. System for Steel Feeding

We have performed the steel feeding through the so-called zig-zag nozzle which has been described previously.\(^1\) With this type of nozzle the steel is distributed to the belt through a row of holes, located before a dam, which is formed by a ceramic bottom plate with a zig-zag profile at its end and the vertical plate of the dam. The system works quite satisfactorily. But, occasionally non-uniform feeding occurred due to clogging of some holes and freezing of steel in the hole. Figure 10 shows the phenomenon. As a result pronounced feeding marks can form at the lower surface of the strand, Fig. 10b. Also the edges of the strand were not filled always due to the unsufficient lateral flow of the melt. To avoid such disturbances a new nozzle design has been developed which is explained in Fig. 11.

The nozzle is a horizontal duct into which the steel enters from the receiving part of the dispenser which is filled with the melt from the furnace/ladle. In the duct there is a siphon made up from a refractory body connected to the roof plate and of a dam connected to the bottom plate. The siphon serves for slag separation and for increasing the steel level. The melt flows over the dam, then downwards over a step towards the belt. A uniform lateral distribution of the melt on the step and on the belt is performed by two rows of argon jets impinging on the liquid steel surface and acting there like a rake. The argon distributors consist of copper bodies in which two channels are machined, one for the argon and the other for cooling water. The argon jets emerge from bores having a pitch of two centimeters. One rake is directed towards the chamfered edge of the ceramic step and the other towards the steel on the belt, at a distance of about 15 cm from the port of the nozzle. Figure 12 shows photos of the feeding area before the casting, Fig. 12a, and during casting, Fig. 12b. The latter photo demonstrates clearly the process of lateral melt distribution performed by the rakes.

The feeding works nicely with this set up and feeding marks like those illustrated in Fig. 10, and incomplete edge filling do not occur any more. There is another advantage of the new system. The thickness of the refractory parts is considerably larger than of those used in the zig-zag nozzle so that the parts can be cut from conventional refractory blocks. Therefore, the new nozzle is much cheaper.

Between the nozzle and the belt there is, for thermal insulation, a layer of fiber material with about 3 mm thickness and an aluminum sheet of 0.5 mm thickness, Fig. 11. The latter is fixed to the frame of the caster and serves to protect
of copper at the strand surfaces.\textsuperscript{7} Due to selective oxidation metallic copper can be precipitated at the strand surfaces which in conventional continuous casting occurs along the austenite grain boundaries sometimes extending into the material for 1 mm or deeper. As a consequence hot brittleness arises which can lead to formation of surface cracks during the casting and/or hot rolling. Since in the single belt process casting and subsequent cooling is under argon there is very little surface oxidation till the strand enters into the roll gap. The oxidation arising then leads to a comparatively thin tarnish layer associated with considerable less copper accumulation. It is believed that due to the inertization and the associated decrease of tarnish formation the single-belt process may be very well suitable for production of flat products from scrap.

In the following some results on the internal porosity, its removal by hot rolling and on the non-metallic inclusion distribution will be presented.

Internal Porosity and Its Removal by Hot Rolling: As has already been mentioned carbon steels must be hot rolled, with a thickness reduction of 60 to 80\%, to achieve the good mechanical properties. The closing of pores by the hot rolling is demonstrated in Fig. 13 which shows a series of micrographs from polished samples taken from the as-cast material (no in-line hot rolling) and from strips which were in-line hot rolled and subsequently off-line hot rolled with various degrees of reduction. Regions with large porosity have been selected for these photographs. There is considerable porosity in the as-cast state, Fig. 13a, but practically no pores are detectable any more after hot rolling with 66\% reduction, Fig. 13d. The process of pore closure is demonstrated quantitatively in Fig. 14 in which the number of structure inhomogeneities (pores, tissures) on an area of 20 mm×10 mm is plotted against the degree of reduction.

The closure of pores has a strong effect on the ductility of the material. Figure 15 shows the usual plot of tensile strength versus elongation. The data points refer to samples with different carbon contents and with different grain size due to different temperatures before hot rolling and different degrees of hot rolling. Hence, a considerable range of elongation and tensile strength is covered. For the as-cast material the elongation values are quite poor (below 10\%) and they fall below the established relationship between tensile strength and elongation\textsuperscript{5} which is the effect of the porosity. As expected the ductility is raised considerably by in-line hot rolling which was with $\varphi=\ln(d_i/d_f)=0.4$ by our single stand rolling facility, and the data points come close to the established relationship. If secondary cooling is applied before in-line rolling most of the data points scatter closely around the known curve. Some samples were off-line rolled from 15 mm to 4 mm ($\varphi=1.3$). The data obtained in this manner are exactly in the range of the known relationship.

Non-metallic Inclusions: As the conventionally cast steel slabs contain non-metallic inclusions so does the product made with the single-belt process. The inclusions in the strand made with our pilot caster were investigated several times with different methods. The results shown in Fig. 16 were obtained with a combination of REM/EDX/picture analysis. They refer to an area of about 13 mm×50 mm taken from the as-cast material of a strand with 0.21\% C,

4. Further Results on Product Quality

In preceding publications\textsuperscript{1–7} we have reported that the internal quality of the product cast with the single belt process is very satisfactory. It was shown that dendrite spacings in carbon steel (and stainless steel) are small compared to those in the interior of conventionally cast steel slabs; and that microsegregation is in the usual range. Macrosegregation is practically absent. Although the different cooling rates at the lower and upper sides of the strand cause non-symmetry of dendrite structure and of microsegregation, this non-symmetry is not reflected in the grain size after hot rolling and there is no significant difference in the mechanical properties (notch impact energy, yield and tensile strength, elongation) and corrosion performance (Strauss and Huey tests) between samples taken from the lower and upper halves of the strand.

There is an interesting phenomenon with the distribution

Fig. 12. Photographs of the feeding area, a) nozzle port with copper distributors for the argon jets, b) distribution of the melt achieved with the argon rakes during a typical experiment.
0.038% Si, 0.57% Mn, 0.004% S, 0.022% Al. The smallest size of detectable inclusion is about 1 μm. Figure 16 gives an evaluation of the data in which the size of the individual Al₂O₃ and SiO₂ inclusions and of other oxide particles is plotted over their spatial coordinates on the investigated surface. It is evident that the inclusions are present more frequently close to the upper surface, as expected, and that they are distributed rather non-uniformly also in the transverse direction.

Inclusions can be detected at the upper strand surface with the scanning electron microscope in pits and crevices which open during pickling with sulfuric acid. Their composition varies widely with the main components being aluminum, silicon, calcium, titanium, manganese, iron. Some of them may consist of almost pure iron oxide indicating that the pit may have been a surface pore which has been oxidized at its surface, or that emulgation of iron oxide droplets may have occurred during the feeding of the steel melt to the belt. Examples are shown in Fig. 17.

Inclusion contents depend on many factors as is well known. The conditions for achieving low levels of oxide inclusions are not so suitable with our pilot caster.

5. Summary and Conclusions

In the present paper the integrated single-belt casting/hot rolling process operated at Clausthal Technical University has been described. Strip casting with in-line hot rolling in-
volving high linear strand/strip velocities and complete coupling of the steps casting/rolling/coiling requires the strict control of the relevant operation parameters. The system used in Clausthal is rather elaborate for a university faculty but certainly not sufficient for a production line which would need more sophisticated controls. The results of our materials investigations were discussed. New data are given on the internal porosity and its removal by hot rolling, and on the content of non-metallic inclusions.

In conclusion it may be stated that the pilot plant in Clausthal operates without major technical difficulties and that most of the product properties are satisfactory. Consequently, the new process seems to be very promising with respect to its industrial application. A similar conclusion has been reached from the results obtained in the parallel project conducted by MEFOS in Sweden.

Nevertheless, there is a number of questions which cannot be investigated with small scale pilot plants and, therefore, cannot be answered at the present time. The questions refer to the machine on one hand and to the product quality on the other hand. In the industrial production of mass steel grades hundreds of tons are being cast over many hours without interruption of the process. It has to be proved that the sufficient geometrical stability of the belt and its guidance system can be attained so that the thickness uniformity of a much wider strand is maintained over many kilometers of the strip. Extending the casting speed to about 1 m s\(^{-1}\) which is that necessary for casting mass steel grades, and to strip widths beyond 1 m require considerable additional development work. With respect to product quality an important question is whether the content of oxide inclusions and their distribution can be controlled, without much additional cost, within the standards existing for the conventionally made products.

These questions and others can be investigated only with a production plant of industrial size. That is, the real potential of the single-belt casting process cannot be assessed unless a full size demonstration plant is built and operated.

For the conclusion of this paper a coil made at the pilot plant in Clausthal, 300 mm wide, 10 mm thick and 15 m long, is shown in Fig. 18.

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![Fig. 17. Examples of oxide inclusions found in crevices at the top surface of the strand after pickling in sulfuric acid. Contents of elements with >5 mass% (contents of elements are related to the sum of the contents of the elements without the content of oxygen).](image1)

![Fig. 18. Typical steel coil manufactured with the Clausthal pilot installation.](image2)