Acta Mechanica Slovaca 28 (2): 22 - 27, Jun 2024
https://doi.org/10.21496/ams.2024.013

Acta Mechanica Slovaca
ISSN 1335-2393
www.actamechanica.sk

Impact of Casting Speed on Low Carbon Steel Manufacturing Process

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Abstract: Presented paper is focused on research of low carbon steel behaviour during continuous casting process. Research was conducted to investigate optimization opportunity of current casting process and possibility of increase in casting speed. Research was focused mainly on primary cooling area which is represented by mould. Mould insert was drilled, and thermocouples were installed in centreline of each side. Among others also temperatures and flow of cooling water, mould insert temperature and surface temperature of billet on the exit from the mould were measured. From conducted research it can be concluded that all following values exhibit strong linear positive or negative progress with increase in casting speed. Heat flux density increases and specific removed heat decreases with adjusted coefficients of determination 0.92 and 0.97. Surface billet temperature after primary cooling increases with adjusted coefficients of determination 0.94. Increase in casting speed also leads to equalization of measured temperatures of mould wall.

Keywords: casting; velocity; heat; transfer; temperature; heat; removal; cooling; steel; carbon

1. Introduction

Intensive research in the field of continuous casting started after second world war as need for steel rapidly grew. Since then, continuous casting of steel became dominant steel production technology except for ingot casting used in production of large forgings. Continuous casting manufacturing process is environmentally as well as economically highly efficient as it allows a constant movement of steel and utilization of residual heat from steel plant in following material processing. In order to achieve high quality and economical production it is crucial to precisely control casting machine, which is a very complex task to perform.

During manufacturing process, it is pivotal to precisely control heat transfer from molten steel in all three cooling zones. The most critical heat transfer takes place in primary cooling, where a solid shell starts to form. Final thickness of solidified shell must be sufficient to withstand all mechanical stresses when it leaves support structure of mould, otherwise a breakout of liquid metal occurs. Secondary cooling consists mainly of water spray with predominantly circular impact patterns [1] and tertiary cooling relies on natural convection and radiation. At the end of casting machine, entire cross section of casted material must be solidified so the whole strip of material can be cut into separated pieces [2] and enter following processing or storage.

Heat transfer taking place in mould must secure solidification of symmetrical shell at outer circumference of casted profile. Rapid increase in shell thickness can be however well observed in corners of casted material as there is the most intense heat removal [3]. Since corners exhibit most significant heat removal, there is a significant gap formation [4, 5] due to shrinkage of material during cooling.

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Local heat transfer from steel into mould and cooling water can exceed 2 $MW.m^{-2}$ [6] and extremes can be obtained during high-speed casting and reach up to 3.2 $MW.m^{-2}$ [7, 8]. The most intense heat transfer occurs in the vicinity of 20 mm below liquid surface [9]. As a result, mould is exposed to a significant thermal load since internal temperatures can reach over 400 °C [10] at the area of shell formation. Thermal load of mould furthermore also intensifies with increase of casting speed [11]. Due to high temperature and imperfect lubrication, there is a significant abrasive and chemical damage of mould. That negatively impacts integrity of mould [12] and can affect heat transfer via mould. Heat transfer is also partially influenced by deformation of mould, that can be well observed in the corners of the mould [13].

Heat transfer via mould is also influenced by type of casted steel. Steels that undergo peritectic reaction also exhibit up to 20 % decrease in heat transfer due to formation of more significant gap in between surface of casted material and mould wall [14, 15]. Once gap is formed, heat transfer is conducted via radiation and convection. Emissivity of steel surface in gap can be within 0.1 to 0.3 if not oxidized, if oxidized it can reach 0.7 [16]. That can be countered via decrease in casting speed [17], drilling of holes into mould [18] or via use of different casting powder [19]. Since peritectic steel shell takes longer to solidify, these steels are prone to subsurface hook formations [20]. Depth of hooks decreases with increase in resistance of shell to warping [21]. During casting of peritectic steels there is a significant risk of breakouts, surface defects and longitudinal cracks [22].

Heat removal can be enhanced by shaping mould inserts to copy shrinkage of cooling steel, especially in corners of the mould [23]. Increase in uniformity of heat removal is also obtained via proper positioning of entry nozzle to mould [24]. Possible clogging of submerged entry nozzle by solidified steel must be prevented by increase of temperature of casted material or by thermal insulation [25], otherwise steel flow can be distorted and impact shell formation.

Natural behaviour of steel in mould can be altered via electromagnetic steering (EMS) or breaking (EMB). EMS can greatly enhance heat transfer via mould which leads to increase in shell thickness [26, 27] and partially can mitigate negative impact of incorrectly cantered entry nozzle [28]. It also enhances removal of impurities and improves grain structure formation [29]. However improper application of EMS can damage shell growth [30] if created flow impacts shell formation area.

Aim of presented work is to investigate and describe impact of casting speed on low carbon steel manufacturing process with focus on heat transfer and related issues such as average heat flux through mould during primary cooling, specific removed heat from casted steel, change of steel surface temperature after primary cooling and progress of temperature profile of mould wall.

2. Experimental work

A measurement was conducted on a radial billet casting machine. Casted profile was 150x 150 mm. Mould insert length was 1 m with 13 mm wall thickness. Cooling water flow was from top of mould to the bottom (see Figure 1). Presented data were obtained during 5.5-hour long continual measurement that were later divided into 512 seconds long time periods. Mean values of measured parameters were calculated for every time period. Obtained mean values are presented in following data.

Distance of liquid steel surface from mould top was measured by ultrasonic sensor. Average distance from mould top of 179 mm was obtained as a mean value with standard deviation of 1.7 mm. Schematic layout of conducted measurement with data inputs can be seen in Figure 1. Collected data was recorded by data logger. Temperature measurements in mould walls were conducted via type K thermocouples positioned at vertical centreline of each mould side. There were installed five thermocouples at distances of 250 mm (3), 400 mm (4), 550mm (5), 700mm (6) and 850mm (7) from the mould top.

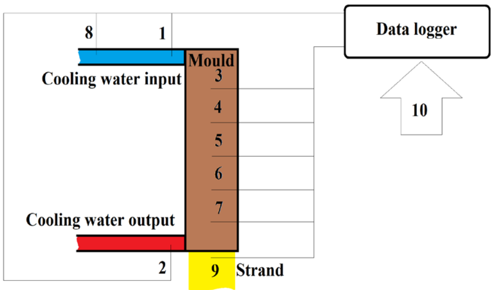

Figure 1: Schematic layout of measurement

Table 1: Chemical composition of researched steel obtained from manufacturer

Value [weight %]	C	Mn	Si	P	S	Cu	Cr	Ni	Mo	V
Minimal	0.068	1.420	0.810	0.012	0.007	0.020	0.040	0.010	0.002	0.004
Maximal	0.079	1.470	0.877	0.016	0.010	0.040	0.060	0.030	0.007	0.005

Among other measured parameters were cooling water temperature on inlet (1) and outlet (2), cooling water volumetric flow rate (8) and billet surface temperature measured by pyrometer (9). Remaining data such as casting speed, chemical composition or steel surface distance from mould top was obtained from casting machine control unit (10). Chemical composition provided by manufacturer of researched steel during conducted measurement is in Table 1. This steel was researched in order to obtain experimental data for optimization of steel manufacturing process setting.

Specific removed heat from billet was calculated as a difference of water enthalpy at the entry of mould and at the exit of mould to the volume of casted steel. This value is expected to provide general information about mould shell thickness. Average heat flux density was obtained as heat flow via surface area of mould below the steel surface.

3. Results

Measured values were processed to obtain empirical values, that can be used for prediction and assessment of continuous casting machine setting. It shall be noted, that obtained numerical values reflect conditions and parameters of measured casting process (casting speed, casted profile, mould geometry, casting powder etc.). Therefore, obtained conclusions are well applicable for casting, that is within measured parameters and production settings.

Methodology for evaluation of measured data is based on assessment of measured values progress with increase in casting speed. Method used for statistical evaluation is a polynomial regression of datapoints via least squares method and corresponding value of adjusted coefficient of determination.

3.1. Heat removal

Progress of heat flux density and specific removed heat values during increase in casting speed can be seen in Figure 2 and 3. Both values exhibit linear behaviour with adjusted coefficients of determination 0.92 and 0.97. Heat flux density exhibits increase with increase in casting speed, however removed specific heat exhibits decrease with increase in casting speed.

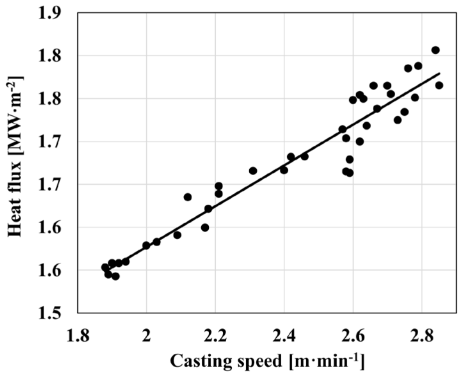

Figure 2: Average heat flux through mould

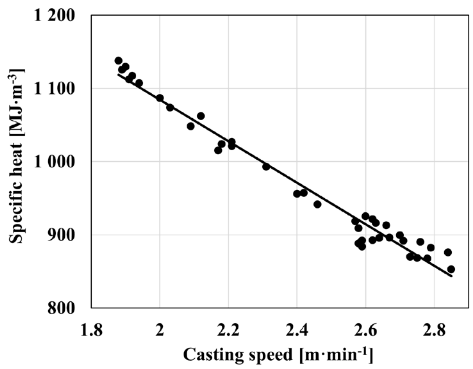

Figure 3: Removed specific heat from steel

3.2. Surface temperature

Billet surface temperature was measured via static pyrometer. Measured surface temperature can be however influenced by occurrence of lower temperature scales on billet surface. Measured surface temperatures for studied steel was in the range from 793 °C to 994 °C. Measured data indicate, that with increase in casting speed there is also increase in measured surface temperature. Adjusted coefficient of determination for a linear regression in Figure 4 is 0.94.

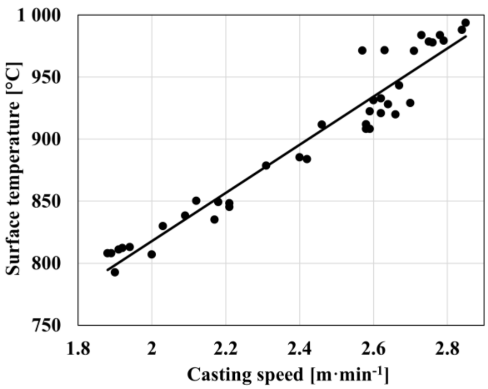

Figure 4: Billet surface temperature

3.3. Mould temperature profile

Temperature profile was measured for every mould wall at the same distance from the top of mould in the centreline of each wall. Presented temperatures were obtained as arithmetic average of temperatures at the same level. Temperatures in all levels exhibit also linear increase with increase of casting speed, however at casting speed above 2.5m.min^{-1} a more significant fluctuation was observed (see Figure 5).

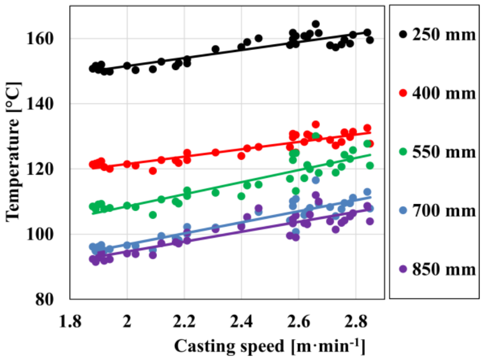

Figure 5: Mould wall temperature

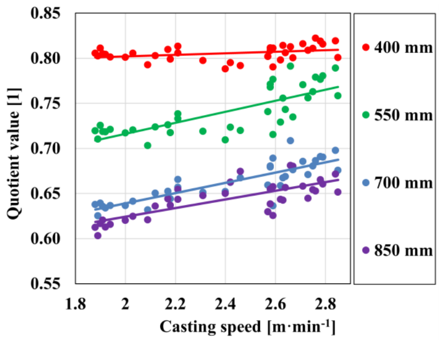

Figure 6: Quotient values

Since the rate of temperature increase on levels 550mm, 700mm and 850mm was observed as higher, another comparison of measured temperatures below level of 250mm to temperature at 250mm was conducted in Figure6. Presented values were obtained as a quotient of measured temperature at specific level to measured temperature at 250mm.

4. Discussion

From obtained results it can be concluded that casting machine operated in area where change of measured parameters to casting speed was linear. However, at casting speeds over 2.5m.min^{-1} a more significant data fluctuation can be observed. Such a fluctuation can be caused by change in one or more conditions of many during casting which eventually influences shell thickness. Casting machine must cope with requested demand for high casting speed while keeping sufficient shell thickness. As a result, casting process must be more often adjusted. For current casting setting a prediction of measured values for higher casting speeds, based on extrapolation from conducted linear regressions, exhibits lower prediction value due to higher data fluctuation that can be observed from casting speed of 2.5m.min^{-1}.

Specific removed heat during casting directly influences shell thickness growth, which is a pivotal criterion for area of primary cooling. Based on obtained values presented in Figure 3 it can be concluded, that specific removed heat from steel decreases with increase in casting speed. That is caused mainly by decrease of time that steel is present in the mould. As a result, an increase of heat flux through mould with increase in casting speed can be observed in Figure 2.

Since increase in casting speed decreases specific removed heat from steel, it was assumed, that billet surface temperature will increase as a result. This assumption was confirmed by pyrometer measurement of billet surface temperature at the exit from the mould. Total observed difference of 201°C can alter physical properties of casting powder in primary cooling zone. Change in temperature of casting powder can influence heat transfer and lubrication. Strength of solidified shell is also significantly temperature dependent. Lower temperatures generally lead to creation of thicker shell. Increase in thickness leads to increase in resistance to mechanical stress. In secondary cooling, surface temperature significantly influences heat transfer into applied water spray since heat transfer increases by order of magnitude once surface temperature drops below occurrence of Leidenfrost effect.

An investigation into change of temperature in mould wall with change in casting speed was conducted. All measured temperatures increased with increase in casting speed in a generally linear trend. However lower area of mould (represented by temperatures at 550mm, 700mm and 850mm) exhibits higher rate of temperature increase compared to higher area (represented by temperatures at 250mm and 400mm). That leads to increase in quotient values of measured temperatures to temperature at 250mm as can be seen in Figure 6. There is only insignificant change in quotient value for level of 400mm, however there is a more significant change of quotient value for lower levels of mould. Therefore, a general trend towards equalization of temperature profile can be observed with increase in casting speed. As previously stated, increase in casting speed increases billet surface temperature and decreases shell thickness and strength. Decrease in strength might lead into decrease of distance between solidified shell and mould surface, since shell is pressed by metalostatic pressure towards mould. It is also assumed that measured temperature change is also response to increase of billet surface temperature at that level.

5. Conclusions

Presented work investigated impact of casting speed on low carbon steel manufacturing process with focus on heat transfer and related issues. Measured parameters were temperature of mould insert wall, water flow and temperature, billet surface temperature and casting speed.

It can be concluded, that casting speed greatly influences heat transfer during casting. Heat flux, specific removed heat from steel and billet surface temperature exhibit high values of adjusted coefficient of linear regression to casting speed, with values over 0.9. However for casting speeds above 2.5 $m.min^{-1}$ these values exhibit more intensive fluctuations.

Increase in casting speed also greatly impacts mould wall temperature. Temperatures increase across the whole length of mould wall. However, there is a noticeable change in temperature gradient in a mould wall. There is an increase in quotient value of measured temperatures to temperature at 250 mm. A less significant increase was observed at 400 mm compared to increase at levels 550 mm, 700 mm and 850mm. It can be concluded that higher casting speed generally results into more equalized temperature profile in mould wall.

Acknowledgments

This paper was created as part of the project No. CZ.02.01.01/00/22_008/0004631 Materials and technologies for sustainable development within the Jan Amos Komensky Operational Program financed by the European Union and from the state budget of the Czech Republic and was supported under Project No. SP2024/025 - Advanced materials and technologies for decarbonization.

References

[1.] PYSZKO, R., PŘÍHODA, M., BURDA, J., FOJTÍK, P., KUBÍN, T., VACULÍK, M., VELIČKA, M., ČARNOGURSKÁ, M. (2013). Cooling nozzles characteristics for numerical models of continuous casting. Metalurgia, 52, 4, 437-440.

[2.] ŠTĚTINA, J., KAVIČKA, F., KATOLICKÝ, J., MAUDER, T., KLIMEŠ, L. (2018). Importance of the experimental investigation of a concasting technology. The Application of Experimental and Numerical Methods in Fluid Mechanics and Energy 2018, 7009.

[3.] SONG, J., CAI, Z., PIAO, F., ZHU, M. (2014). Heat Transfer and Deformation Behavior of Shell Solidification in Wide and Thick Slab Continuous Casting Mold. Journal of Iron and Steel Research, International, 21, 1, 1-9.

[4.] PYSZKO, R. (2015). Diagnostika procesu plynulého odlévání oceli. VŠB - Technická univerzita Ostrava, Ostrava.

[5.] RAY, K., BASAK, I. (2018). Local heat flux profiles and interfacial thermal resistance in steel continuous casting. Journal of Materials Processing Technology, 255, 605-610.

[6.] UDAYRAJ, S.C., GANGULY, S., CHACKO, E.Z., AJMANI, S.K., TALUKDAR, P. (2017). Estimation of surface heat flux in continuous casting mould with limited measurement of temperature. International Journal of Thermal Sciences, 118, 435-447.

[7.] JEONG, H., HWANG, J., CHO, J. (2016). In-depth study of mold heat transfer for the high speed continuous casting process. Metals and Materials International, 22, 2, 295-304.

[8.] VAKA, A. S., GANGULY, S., TALUKDAR, P. (2021). Novel inverse heat transfer methodology for estimation of unknown interfacial heat flux of a continuous casting mould: A complete three-dimensional thermal analysis of an industrial slab mould. International Journal of Thermal Sciences, 160, 106648.

[9.] WU, H., CHEN, J., PENG, Z. (2020). Simulation of the flow-heat transfer process in billet mold and analysis of the billet rhomboidity phenomenon. Applied Thermal Engineering, 173, 115235.

[10.] KIL PARK, J., SAMARASEKERA, I.V., THOMAS, B.G., YOON, U.S. (2000). Analysis of thermal and mechanical behavior of copper mould during thin slab casting. 83rd Steelmaking Conference Proceedings, 9-21.

[11.] ZHANG, X., JIANG, Z., ZHANG, Q., DOU, C. (2011). Investigation of Thermal Performance of Mold Copper Plate in Slab Continuous Casting. The Open Mechanical Engineering Journal, 14, 5, 39-42.

[12.] SRNEC NOVAK, J., LANZUTTI, A., BENASCIUTTI, D., DE BONA, F., MORO, L., DE LUCA, A. (2018). On the damage mechanisms in a continuous casting mold: After-service material characterization and finite element simulation. Engineering Failure Analysis, 94, 480-492.

[13.] DU, F., WANG, X., LIU, Y., LI, T., YAO, M. (2016). Analysis of Non-uniform Mechanical Behavior for a Continuous Casting Mold Based on Heat Flux from Inverse Problem. Journal of Iron and Steel Research, International, 23, 2, 83-91.

[14.] SINGH, S.N., BLAZEK, K.E. (1974). Heat transfer and skin formation in a continuous-casting mold as a function of steel carbon content. JOM, 26, 10, 17-27.

[15.] PYSZKO, R., PŘÍHODA, M., VELIČKA, M. (2010). Methods for determining the thermal boundary condition in the CC mould for numeric models. Conference proceedings - METAL 2020, 35-40.

[16.] MILLS, K.C., KARAGADDE, S., LEE, P.D., YUAN, L., SHAHBAZIAN, F. (2016). Calculation of Physical Properties for Use in Models of Continuous Casting Process-Part 2: Steels. ISIJ International 56, 2, 274-281.

[17.] EMI, T., FREDRIKSSON, H. (2005). High-speed continuous casting of peritectic carbon steels. Materials Science and Engineering: A, 413-414, 2-9.

[18.] MIZUKAMI, H., SHIRAI, Y., HIRAKI, S. (2020). Initially Solidified Shell Growth of Hypo-peritectic Carbon Steel in Continuous Casting Mold. ISIJ International, 60, 9, 1968-1977.

[19.] LONG, X., LONG, S., LUO, W., LI, X., TU, C., NA, Y., XU, J. (2023). Crystallization of Slag Films of CaO-Al2O3-BaO-CaF2-Li2O-Based Mold Fluxes for High-Aluminum Steels' Continuous Casting. Materials, 16, 5, 1903.

[20.] SHIN, H., LEE, G., CHOI, W., KANG, S., PARK, J. KIM, S., THOMAS, B.G. (2004). Effect of Mold Oscillation on Powder Consumption and Hook Formation in Ultra Low Carbon Steel Slabs. AISTech - Iron and Steel Technology Conference Proceedings, 1157-1170.

[21.] WANG, W., ZHU, C., ZHOU, L. (2017). Initial Solidification and Its Related Heat Transfer Phenomena in the Continuous Casting Mold. Steel research international, 88, 10, 1600488.

[22.] AZIZI, G., THOMAS, B.G., ASLE ZAEEM, M. (2020). Review of Peritectic Solidification Mechanisms and Effects in Steel Casting. Metallurgical and Materials Transactions B, 51B, 5, 1875-1903.

[23.] YU, S., LONG, M., ZHANG, M., CHEN, D., XU, P., DUAN, H., YANG, J. (2021). Effect of mold corner structures on the fluid flow, heat transfer and inclusion motion in slab continuous casting molds. Journal of Manufacturing Processes, 68A, 1784-1802.

[24.] ZHANG, W., GAO, J., ROHATGI, P.K., ZHAO, H., LI, Y. (2009). Effect of the depth of the submerged entry nozzle in the mold on heat, flow and solution transport in double-stream-pouring continuous casting. Journal of Materials Processing Technology, 209, 15-16, 5536-5544.

[25.] VAKHRUSHEV, A., KHARICHA, A., WU, M., LUDWIG, A., TANG, Y., HACKL, G., NITZL, G., WATZINGER, J., BOHACEK, J. (2021). On Modelling Parasitic Solidification Due to Heat Loss at Submerged Entry Nozzle Region of Continuous Casting Mold. Metals, 11, 9, 1375.

[26.] LI, X., ZHANG, Z., LV, M., FANG, M., MA, S., LI, D., XI, X. (2023). Effect of Mold Electromagnetic Stirring on Metallurgical Behavior in Ultrahigh Speed Continuous Casting Billet Mold. Steel research international, 94, 6, 2200796.

[27.] YAO, C., WANG, M., ZHANG, M., XING, L., ZHANG, H., BAO, Y. (2022). Effects of mold electromagnetic stirring on heat transfer, species transfer and solidification characteristics of continuous casting round billet. Journal of Materials Research and Technology, 19, 1766-1776.

[28.] WANG, J., QIU, G., ZHU, J., WANG, W., YANG, Y., LI, X., LIU, C. (2023). Effect of Nozzle Position on Fluid Flow and Solidification in a Billet Curved Mould using Mould Electromagnetic Stirring. Steel research international, 94, 3, 2200536.

[29.] CHO, S., THOMAS, B.G. (2020). Electromagnetic Effects on Solidification Defect Formation in Continuous Steel Casting. JOM, 72, 10, 3610-3627.

[30.] MAURYA, A., JHA, P.K. (2017). Influence of electromagnetic stirrer position on fluid flow and solidification in continuous casting mold. Applied Mathematical Modelling 48, 736-748.