APEM journal

Advances in Production Engineering & Management
Volume 18 | Number 4 | December 2023 | pp 501–511
https://doi.org/10.14743/apem2023.4.488

ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

Reduction of surface defects by optimization of casting speed using genetic programming: An industrial case study

Kovacic, M.[a,b,c,*], **Zuperl, U.**[d], **Gusel, L.**[d], **Brezocnik, M.**[d]

[a]ŠTORE STEEL, d.o.o., Research and Development, Štore, Slovenia
[b]University of Ljubljana, Faculty of Mechanical Engineering, Laboratory for Fluid Dynamics and Thermodynamics, Ljubljana, Slovenia
[c]College of Industrial Engineering, Celje, Slovenia
[d]University of Maribor, Faculty of mechanical engineering, Maribor, Slovenia

ABSTRACT

Štore Steel Ltd. produces more than 200 different types of steel with a continuous caster installed in 2016. Several defects, mostly related to thermomechanical behaviour in the mould, originate from the continuous casting process. The same casting speed of 1.6 m/min was used for all steel grades. In May 2023, a project was launched to adjust the casting speed according to the casting temperature. This adjustment included the steel grades with the highest number of surface defects and different carbon content: 16MnCrS5, C22, 30MnVS5, and 46MnVS5. For every 10 °C deviation from the prescribed casting temperature, the speed was changed by 0.02 m/min. During the 2-month period, the ratio of rolled bars with detected surface defects (inspected by an automatic control line) decreased for the mentioned steel grades. The decreases were from 11.27 % to 7.93 %, from 12.73 % to 4.11 %, from 16.28 % to 13.40 %, and from 25.52 % to 16.99 % for 16MnCrS5, C22, 30MnVS5, and 46MnVS5, respectively. Based on the collected chemical composition and casting parameters from these two months, models were obtained using linear regression and genetic programming. These models predict the ratio of rolled bars with detected surface defects and the length of detected surface defects. According to the modelling results, the ratio of rolled bars with detected surface defects and the length of detected surface defects could be minimally reduced by 14 % and 189 %, respectively, using casting speed adjustments. A similar result was achieved from July to November 2023 by adjusting the casting speed for the other 27 types of steel. The same was predicted with the already obtained models. Genetic programming outperformed linear regression.

ARTICLE INFO

Keywords:
Continuous casting of steel;
Surface defects;
Automatic control;
Machine learning;
Modelling;
Optimization;
Prediction;
Linear regression;
Genetic programming

**Corresponding author:*
miha.kovacic@store-steel.si
(Kovacic, M.)

Article history:
Received 3 November 2023
Revised 15 December 2023
Accepted 21 December 2023

References

[1] Emi, T., Fredriksson, H. (2005). High-speed continuous casting of peritectic carbon steels, *Materials Science and Engineering*: *A*, Vol. 413-414, 2-9, doi: 10.1016/j.msea.2005.08.169.
[2] Santos, C.A., Spim, J.A., Ierardi, M.C., Garcia, A. (2002). The use of artificial intelligence technique for the optimisation of process parameters used in the continuous casting of steel, *Applied Mathematical Modelling*, Vol. 26, No. 11, 1077-1092, doi: 10.1016/S0307-904X(02)00062-8.
[3] Boonpen, K., Kowitwarangkul, P., Ninpetch, P., Phophichit, N., Chuchuay, P., Threrujirapapong, T., Otarawanna, S. (2021). Numerical study of influence of casting speed on fluid flow characteristics in the four strand tundish, *Materials Today: Proceedings*, Vol. 47, Part 12, 3480-3486, doi: 10.1016/j.matpr.2021.03.465.
[4] Hore, S., Das, S.K., Humane, M.M., Peethala, A.K. (2019). Neural network modelling to characterize steel continuous casting process parameters and prediction of casting defects, *Transactions of the Indian Institute of Metals*, Vol. 72, No. 12, 3015-3025, doi: 10.1007/s12666-019-01767-0.

[5] Fei, P., Min, Y., Liu, C.-J., Jiang, M.-F. (2019). Effect of continuous casting speed on mold surface flow and the related near-surface distribution of non-metallic inclusions, *International Journal of Minerals, Metallurgy, and Materials*, Vol. 26, No. 2, 186-193, doi: 10.1007/s12613-019-1723-y.
[6] Swain, A.N.S.S., Ganguly, S., Sengupta, A., Chacko, E.Z., Dhakate, S., Pandey, P.K. (2022). Investigation of corner cracks in continuous casting billet using thermomechanical model and plant measurements, *Metals and Materials International*, Vol. 28, No. 10, 2434-2447, doi: 10.1007/s12540-021-01135-y.
[7] Zhu, L.-G., Kumar, R.V. (2007). Modelling of steel shrinkage and optimisation of mould taper for high speed continuous casting, *Ironmaking & Steelmaking*, Vol. 34, No. 1, 76-82, doi: 10.1179/174328106X118152.
[8] Alizadeh, M. (2015). Study on hot tearing tendency during continuous casting of steel by overall hot tearing susceptibility (OHTS), *International Journal of Cast Metals Research*, Vol. 28, No. 1, 20-27, doi: 10.1179/1743133614Y.0000000124.
[9] Furumai, K., Aramaki, N., Oikawa, K. (2022). Influence of heat flux different between wide and narrow face in continuous casting mould on unevenness of hypo-peritectic steel solidification at off-corner, *Ironmaking & Steelmaking*, Vol. 49, No. 9, 845-859, doi: 10.1080/03019233.2022.2063654.
[10] Sala, D.A., Van Yperen-De Deyne, A., Mannens, E., Jalalvand, A. (2023). Hybrid-input FCN-CNN-SE for industrial applications: Classification of longitudinal cracks during continuous casting, *Metals*, Vol. 13, No. 10, Article No. 1699, doi: 10.3390/met13101699.
[11] Kong, Y., Chen, D., Liu, Q., Long, M. (2019). A prediction model for internal cracks during slab continuous casting, *Metals*, Vol. 9. No. 5, Article No. 587, doi: 10.3390/met9050587.
[12] Zhang, T., Yang, J., Jiang, P. (2019). Measurement of molten steel velocity near the surface and modeling for transient fluid flow in the continuous casting mold, *Metals*, Vol. 9, No. 1, Article No. 36, doi: 10.3390/met9010036.
[13] Kovačič, M., Jager, R. (2015). Modeling of occurrence of surface defects of C45 steel with genetic programming, *Materiali in tehnologije/Materials and technology,* Vol. 49, No. 6, 857-863, doi: 10.17222/mit.2013.304.
[14] Tran, H.-S., Castiaux, E., Habraken, A.-M. (2020). 2D thermal finite element analysis of sticker breakout in continuous casting, *Procedia Manufacturing*, Vol. 50, 376-383, doi: 10.1016/j.promfg.2020.08.069.
[15] He, F., Zhou, L., Deng, Z.-H. (2015). Novel mold breakout prediction and control technology in slab continuous casting, *Journal of Process Control*, Vol. 29, 1-10, doi: 10.1016/j.jprocont.2015.03.003.
[16] Santos, C.A., Spim, J.A., Ierardi, M.C.F., Garcia, A. (2002). The use of artificial intelligence technique for the optimisation of process parameters used in the continuous casting of steel, *Applied Mathematical Modelling*, Vol. 26, No. 11, 1077-1092, doi: 10.1016/S0307-904X(02)00062-8.
[17] Tao, J., Wang, N. (2005). Fuzzy neuron hybrid control for continuous steel casting, *IFAC Proceedings Volumes*, Vol. 38, No. 1, 121-126, doi: 10.3182/20050703-6-CZ-1902.01699.
[18] Zhang, Q.-Y., Wang, X.-H. (2010). Numerical simulation of influence of casting speed variation on surface fluctuation of molten steel in mold, *Journal of Iron and Steel Research International*, Vol. 17, No. 8, 15-19, doi: 10.1016/S1006-706X(10)60121-5.
[19] Vertnik, R., Mramor, K., Šarler, B. (2019). Solution of three-dimensional temperature and turbulent velocity field in continuously cast steel billets with electromagnetic stirring by a meshless method, *Engineering Analysis with Boundary Elements*, Vol. 104, 347-363, doi: 10.1016/j.enganabound.2019.03.026.
[20] Šarler, B., Vertnik, R., Šaletić, S., Manojlović, G., Cesar, J. (2005). Application of continuous casting simulation at štore steel, *BHM Berg- und Hüttenmännische Monatshefte*, Vol. 150, No. 9, 300-306, doi: 10.1007/BF03165327.
[21] Gryc, K., Smetana, B., Žaludová, M., Michalek, K., Klus, P., Tkadlečková, M., Socha, L., Dobrovská, J., Machovčák, P., Válek, L., Pachlopnik, R., Chmiel, B. (2013). Determination of the solidus and liquidus temperatures of the real-steel grades with dynamic thermal-analysis methods, *Materiali in tehnologije/Materials and technology,* Vol. 47, No. 5, 565-575.
[22] Bhoskar, T., Kulkarni, O.K., Kulkarni, N.K., Patekar, S.L., Kakandikar, G.M., Nandedkar, V.M. (2015). Genetic algorithm and its applications to mechanical engineering: A review, *Materials Today: Proceedings*, Vol. 2, No. 4-5, 2624-2630, doi: 10.1016/j.matpr.2015.07.219.
[23] Jha, R., Pettersson, F., Dulikravich, G.S., Saxen, H., Chakraborti, N. (2015) Evolutionary design of nickel-based superalloys using data-driven genetic algorithms and related strategies, *Materials and Manufacturing Processes,* Vol. 30, No. 4, 488-510, doi: 10.1080/10426914.2014.984203.
[24] Gajsek, B., Dukic, G., Kovacic, M., Brezocnik, M. (2021). A multi-objective genetic algorithms approach for modelling of order picking, *International Journal of Simulation Modelling,* Vol. 20, No. 4, 719-729, doi: 10.2507/IJSIMM20-4-582.
[25] Tuzkaya, U.R., Şahin, S. (2021). A single side priority based ga approach for 3D printing center integration to spare part supply chain in automotive industry, *Tehnički Vjesnik – Technical Gazette,* Vol. 28, No. 3, 836-844, doi: 10.17559/TV-20200311104539.
[26] Liu, M.L., Yao, X.Z., Huang, J.Y., Zhang, C. (2022). Optimization of unmanned vehicle scheduling and order allocation, *International Journal of Simulation Modelling,* Vol. 21, No. 3, 477-488, doi: 10.2507/IJSIMM21-3-613.
[27] Chen, D., Zhao, X.R. (2021). Production management of hybrid flow shop based on genetic algorithm, International Journal of Simulation Modelling, Vol. 20, No. 3, 571-582, doi: 10.2507/IJSIMM20-3-CO12.
[28] Grubeša, S., Suhanek, M., Djurek, I., Petošić, A. (2021). Combination of boundary element method and genetic algorithm for optimization of T-shape noise Barrier, *Tehnički Vjesnik – Technical Gazette,* Vol. 28, No. 1, 77-81, doi: 10.17559/TV-20190930132137.
[29] Koza, J.R. (1992). *Genetic programming: On the programming of computers by means of natural selection*, MIT Press Cambridge, USA.
[30] Koza, J.R. (1994). *Genetic programming II: Automatic discovery of reusable programs,* MIT Press, Cambridge, USA.

[31] Koza, J.R., Andre, D., Bennett, F.H., Keane, M.A. (1999). Genetic programming III: Darwinian invention and problem solving [book review], *IEEE Transactions on Evolutionary Computation,* Vol. 3, No. 3, 251-253, doi: 10.1109/TEVC.1999.788530.
[32] Kovacic, M., Brezocnik, M. (2018). Reduction of surface defects and optimization of continuous casting of 70MnVS4 steel, *International Journal of Simulation Modelling,* Vol. 17, No. 4, 667-676, doi: 10.2507/IJSIMM17(4)457.
[33] Kovačič, M., Župerl, U. (2023). Continuous caster final electromagnetic stirrers position optimization using genetic programming, *Materials and Manufacturing Processes*, Vol. 38, No. 16, 2009-2017, doi: 10.1080/10426914.2023.2219317.
[34] Kovačič, M., Župerl, U. (2022). Modeling of tensile test results for low alloy steels by linear regression and genetic programming taking into account the non-metallic inclusions, *Metals*, Vol. 12, No. 8, Article No. 1343, doi: 10.3390/met12081343.
[35] Kovačič, M., Šarler, B. (2011). Genetic programming and soft-annealing productivity, *Materiali in tehnologije/Materials and technology,* Vol. 45, No. 5, 427-432.
[36] Kovačič, M., Župerl, U. (2020). Genetic programming in the steelmaking industry*, Genetic Programming and Evolvable Machines,* Vol. 21, No. 1-2, 99-128, doi: 10.1007/s10710-020-09382-5.