EUROPEAN COOPERATION IN THE FIELD OF SCIENTIFIC AND TECHNICAL RESEARCH - COST

COST 526

Automatic Process Optimization in Materials Technology

(APOMAT)

Title:

Modelling and Optimization for Competitive Continous Casting

Keywords: steel, continuous casting, process simulator, metallurgical cooling criteria, optimisation problem

Organization/Company:
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1. Duration / run time of the project

01.07.2000 to 30.06.2004

2. Overall cost

6 man year: 6 × 50 kEURO = 300 kEURO

3. Funding situation

2-man year already assured from governmental support (COST-526) and involved industry.
Applications for the remaining 2/3 of project budget underway.

4. Project partners indicated to participate

National partners

1. Prof. Bogdan Filipi• (project leader), Department of Intelligent Systems,
Jo ef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia.

2. Darko Mikec, M.Sc. (project leader), Research and Development, ACRONI Jesenice,
Cesta Borisa Kidri•a 44, SI-4270 Jesenice, Slovenia.

3. Gojko Manojlovi•, B.Sc. (project leader), Technical Development, INEXA-Štore,
elezarska cesta 3, SI-3220 Štore, Slovenia.

International partners

1. Prof. Erkki Laitinen (project leader), Valtteri Toivonen, M.Sc., Mika Rekkilä, M.Sc.
University of Oulu, Department of Mathematical Sciences,
P.O.Box. 3000, FIN-90014 Oulu, Finland
with Finnish national partners:
Dr. Seppo Louhenkilpi, Helsinki University of Technology,
Dr. Joachim Wendt, VTT Manufacturing Technology

Industrial partner:

Rautaruuki Raahe Steelworks, Finland

2. Prof. Miroslav Raudenský (project leader), Prof. Jaroslav Horský, Ludek Telecký, B.Sc., Zuzana Vetesnikova

Fluid Flow and Heat Transfer Laboratory, Institute of Aerospace Engineering, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2, 61669 Brno,

Czech Republic

Industrial partners:

Steelworks Vitkovice, Ostrava, Czech Republic

Steelworks Nova-Hut, Ostrava, Czech Republic

Steelworks T•inec, T•inec, Czech Republic

Description of collaborative approach:

During the last 10 years the Slovenian research team developed detailed numerical heat transfer models of the continuous casting process for billets and slabs and successfully applied them in real industrial environments for simulating steady-state and transient conditions. In addition to the simulator, a basic set of object functions and genetic algorithm-based optimizer have been experimentally employed. For this purpose, the collaboration with the Finnish group was essential and led towards improvements in numerical models and integration of the IDS steel material properties package. The collaboration with the Czech group was established primarily for measurements in industrial and laboratory environments. The simulators subsequently use plant-specific heat transfer correlation. The object functions have been developed together with industrial partners who will continue to deliver all necessary process information, assist in model adaptation and finally use the automatic optimization software. The collaboration between involved national and international partners is already well established and will be continued in this project.

Mutual befits of the involved research teams are: joint development, dissemination, exploitation of automatic optimization techniques, which can also be used in other technologies.

Mutual benefits of the involved end-users: improved high-quality slabs and billets, modification of the secondary cooling systems, energy and cooling water savings, increased competitiveness.

5. Project partners to be found

Proposals of other research institutions and manufacturing companies to join the initial three (CZ-SF-SI) projects cluster are welcome.

6. Short description of the material process to be optimized

The world steel production is around 750 million tons per year. The European Community is producing about 20 percent of this amount and shares more than 30 percent of the income due to comparatively advanced technology and product quality. The present project is going to develop (pre)competitive knowledge for strengthening these advantages. Continuous casting is currently the most common casting practice in ferrous metallurgy. The process involves molten steel being fed through a bottomless water-cooled mould where it is sufficiently solidified around the outer surface that it takes over the shape of the mould and acquires sufficient mechanical strength to contain the molten core at the centre. The strand is pulled from the mould with a system of rolls, and cooled by the spray system. The continuous casting is being substantially upgraded in order to widen the grades and shapes of the produced billets, blooms, slabs and rounds, to increase the quality of the product and productivity of the process. The computational modelling of the process is becoming increasingly powerful tool for help in basic machine design calculations, identifying and quantifying the mechanisms of various types of defects, troubleshooting the origin of particular defects, and optimizing the various process conditions to increase the productivity or minimize the defect.

7. Material(s) involved:

Steel (broad spectra of grades) in the form of billets (INEXA) and slabs (ACRONI).

8. Optimization potential of the process or process step

The quality of continuously cast strands is determined by the desired composition and cleanness of the melt, by the expected shape and surface smoothness of the final product, and by the low as possible cracking, and macro- and micro-segregation. It turns out that the majority of the defects can be avoided by proper cooling strategy. The main aim of this proposal is to develop a computational framework for automatic prediction of optimum process parameters setting, particularly the cooling conditions. Most of previous advances have been based entirely on the empirical knowledge gained from experimentation with the process. Present approach combines empirical knowledge which results in the definition of optimisation criteria, computational heat transport model of the process, and optimisation procedure. The continuous casting process has a substantial optimisation potential because the process involves many input parameters which are almost impossible to set optimally through experimentation only. Both involved Slovenian companies produce small amounts of very broad spectra of different high quality steel grades, i.e. the optimization potentials are even more pronounced. They estimate reduction of scrap rate up to 10%, reduction of cooling water amount up to 5%, reduction in energy savings up to 10%.

9. Specified material properties to be achieved

The continuously cast steel should be cast in a safe, defect-free, and economic way. The cost function, composed for the mentioned three process characterization categories will be deduced. The corresponding weights will be adjusted according to the steel grade and product preferences. The possible set of safety criteria include maximum safety depth of the liquid pool, minimum shell thickness at the end of the mould. The possible set of quality criteria include maximum quality depth of the liquid pool, maximum strand surface cooling/reheating rate in spray cooling zone, maximum strand surface temperature in unbending region, maximum positive/negative strand surface temperature deviation at given axial position in spray cooling zone. The possible set of economic criteria include minimum casting speed and maximum superheat.

10. Process parameters to be optimized

The heat flux from the strand to the caster cooling system will be optimised. Related process parameters, such as casting speed, casting velocity, mould settings (taper, powder, copper plate flows), and secondary cooling spray flows will be optimised. The last task will be split into following two tasks:

(1) Secondary cooling system geometry and nozzle types are predetermined.

(1.a) Operational optimization in steady-state conditions: what are the optimum spray flows for a given steel grade and format? Used in optimum set-up of secondary cooling system.

(1.b) Operational optimization in transient conditions: what are the optimum spray flows and other casting conditions, such as casting speed, in operational transients?

(2) Secondary cooling system and nozzles types are not predetermined.

Design optimization: what are the optimum secondary cooling system geometry, spray flow range, and nozzle types for casting given family of steel grades and formats? Used in design modifications of the secondary cooling system.

11. Material laws including material dependent coefficients

Like most commercial materials processes, the continuous casting involves many interacting phenomena of great complexity. Because of this complexity, no model can include all of the phenomena at once. The transient three-dimensional mixture-continuum heat transport model of the strand will be considered with caster specific mould cooling correlation, spray system set of correlation, roll cooling set of correlation, and radiation. The convection in the melt will be heuristically incorporated into effective thermal conductivity. The temperature dependent material properties (density, thermal conductivity, specific heat, liquid fraction) will be taken from the collaboration with the Finnish group. The measured temperature dependent heat transfer correlation will be obtained from the collaboration with the Czech group. It is believed that the described (properly calibrated to specific caster) simple model reasonably represents the key heat transfer phenomena of the process.

12. Simulator

Numerical evaluation of the described model is performed iteratively through transformation of the governing equation into source term form, Crank-Nicolson time discretization, Voller-Swaminathan timestepping strategy, and the classical Patankar finite volume method. The solution in three dimensions is performed with operator splitting. Non-uniform meshing in axial direction is used to properly describe the heat transfer around roll contacts. From the calculated temperature data, individual values of the optimisation criteria are numerically derived, based on their formulation in terms of strand temperatures.

Two versions of simulator are available: two-dimensional time dependent version for on-line optimization and three-dimensional steady-state for off-line optimization. The computing time of one simulation is several seconds for the transient version and several minutes for the more detailed steady-state version. This allows the generation of many solutions in a reasonable time, which is crucial in optimization process.

13. Optimizer

The primary task of this project represents further development and calibration of the simulator and proper, steel specific definition of optimization criteria, and proper definition of optimization problem as a whole. The optimizer, based on hybrid evolutionary computation approach will be used, developed by the collaborating domestic and foreign partners (see their project proposals). A standard interface simulator-optimizer will be developed, allowing to couple different caster simulators with different optimizers.

14. Competence / activities of proposer:

The proposer is already involved in automatic process optimization of the steel continuous casting. The basic computational infrastructure including the simulator, optimization criteria, optimization problem, and optimization algorithm have been already developed. The main aim of the present proposal is to improve the overall performance of the system, to improve the optimization criteria, to modify the optimization criteria with respect to the specific steel grade, and to transfer the state-of-the-art of the system from the initial into (pre)competitive phase.

15. International state of the art and references

Not many related attempts are known to the present proposer. The discipline of computer optimization of process parameters in continuous casting of steel started in late Eighties by Laitinen [IR 7] by using finite difference method for evaluation of the heat transfer model and conjugate gradient methods for solving the related optimization problem. Similar numerical heat transfer model has been used by Lally, Biegler and Henein [IR 8, IR 9] in the beginning of Nineties, however they use successive quadratic programming for solving the optimization problem. Grever, Binder, Engl and Mörwald recently solve [IR 10] the dynamic optimization problem for spray setting which ensures the solidification takes place in the soft reduction zone regardless on the changes in casting speed. For solving the optimization problem they use the Quasi-Newton method. Very recently, Šarler, Filipi•, Raudenský, Horský and Šubelj use the finite volume based numerical heat transfer model together with the genetic algorithm based optimization procedure [IR 4, IR 5, IR 6] for optimal setting of continuous casting parameters. The automatic optimization of process parameters in continuous casting of steel is quickly expanding interdisciplinary field [IR 11, IR 12]. All related publications mainly work out the methodology, which is lacking feedback from systematic experimental evidence. This justifies the listed proposed project activities.

International references

IR 1. W.R. Irwing, Continuous Casting of Steel, The University Press, Cambridge, 1993.

IR 2. B.G. Thomas, C. Beckermann (eds.), Modelling of Casting Welding and Advanced Solidification Processing VIII, TMS, Warrendale, 1998.

IR 3. B. Šarler, H. Power, C.A. Brebbia (eds.), Computational Modelling of Free and Moving Boundary Problems V, WIT Press, Southampton and Boston, 1999.

IR 4. J.K. Brimacombe, I.V. Samarasekera, Fluid flow and heat transfer in steel continuous-casting systems, Y. Sahai, G.R. St.Pierre (eds.), Advances in Transport Processes in Metallurgical Systems, Elsevier, 1992, pp. 327-386.

IR 5. M. Rappaz, M. Kedro (ed.), Proceedings of the General COST-512 Workshop on Modelling in Materials Science and Processing, EPFL, Lausanne 1996.

IR 6. C. Avello, J.I. Bartolomé, J. Palacios (eds.), Third European Continuous Casting Conference, UNESID, Madrid, 1998.

IR 7. E. Laitinen, On the Simulation and Control of the Continuous Casting of Steel, Ph.D. Thesis, University of Jyväskylä, Finland, 1989.

IR 8. B. Lally, L.T. Biegler, H. Henein, Optimization and continuous casting, Part I. Problem formulation and solution strategy, *Met.Trans*., **22b**, 1991, pp. 641-648.

IR 9. B. Lally, L.T. Biegler, H. Henein, Optimization and continuous casting, Part II. Application to industrial casters, *Met.Trans*., **22b**, 1991, pp. 649-659.

IR 10. W. Grever, A. Binder, H.W. Engl, K. Mörwald, Optimal cooling strategies in continuous casting of steel with variable casting speed, Inverse Problems in Engineering, **2**, 1997, pp. 289-300.

IR 11. N. Cheung, A. Garcia, The use of heuristic technique for the optimization of quality of steel billets produced by continuous casting, *Artificial Intelligence*, **14**, 2001, pp. 229-238.

IR 12. N. Chakraboti, R. Kumar, D. Jain, A study of the continuous casting mold using a pareto-converging genetic algorithm, *Applied Mathematical Modelling*, **25**, 2001, pp. 287-297.

Domestic references

DR 1. B. Šarler, G. Kuhn, R. Białecki, DRBEM solution of mass and momentum transport in solidification, *Z.Angew.Math.Mech*., 79, 1999, pp. S745-S746.

DR 2. B. Šarler, J.Mencinger, Solution of temperature field in D.C. cast aluminium alloy billet by the dual reciprocity boundary element method, *Int.J.Numer Methods Heat Fluid Flow*, 9, 1999, pp. 269-295.

DR 3. B.Šarler, Dual reciprocity boundary element method solution of the continuous casting problem, J.I. Frankel, C.A. Brebbia, M.A.H. Aliabadi, (eds.), *Boundary Element Technology XII*, 1997, pp. 309-320.

DR 4. B. Šarler, B. Filipič, Continuous casting simulator - a tool for improved quality and productivity, G.Pindor (ed.), International Conference on Continuous Casting of Billets, Czech Metallurgical Society, Trinec, 1997.

DR 5. B. Flipič, B. Šarler, E. Šubelj, Evolutionary optimization of continuous casting at the ACRONI (Slovenia) steelworks, *EvoNews*, 2, 1996, pp. 16-18.

DR 6. B. Šarler, B. Filipič, M. Raudenský, J. Horský, An interdisciplinary approach towards optimum continuous casting of steel, V.R. Voller, H. Henein (eds.), Materials Processing in the Computer Age III (chapter with keynote and invited papers), TMS, Warrendale, 2000, pp. 27-36.