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Optimization of the rhomboidity of continuously cast billets using linear regression and genetic programming: A real industrial study

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A B S T R A C T

During the continuous casting of steel billets, several geometrical, inner and surface defects can occur due to the thermomechanical behavior during solidification. One of them is rhombic distortion (i.e. rhomboidity), which can lead to the occurrence of off-corner cracks and twisting of cast billets during further plastic deformation (i.e. rolling). Based on data of 2088 cast batches (64 different hypoeutectoid steel grades), 109,514 billets, produced from January 2022 to September 2022 in Štore Steel Ltd. (Slovenia), chemical composition (content of C, Si, Mn, S, Cr, Mo, Ni and V), casting parameters (average casting temperature, average difference between input and output cooling water, melt level, average cooling water flow and pressure in the first and second zone of secondary cooling) the linear regression and genetic programming were used in order to predict rhomboidity of continuously cast billets. The rhomboidity, in our case defined as relative diagonal difference, was determined using in-house developed computer vision system for measuring of rhomboidity. Based on the modelling results 9 batches (419 billets) of 42CrMos4 were cast in September 2022 with a 10 % higher water pressure in the first zone of secondary cooling (from 2.41 bar to 2.67 bar). The rhomboidity of continuously cast billets improved by 18.18 % (from 1.43 % to 1.21).

A R T I C L E   I N F O

Keywords:
Continuous casting of steel;
Casting defects;
Rhombic distortion;
Rhomboidity;
Machine learning;
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Prediction;
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1. Introduction

Continuous casting, as one of the most important processes in the modern steel industry, takes place when the melt cools rapidly while passing through a copper mould in a horizontal or vertical direction. During primary cooling, the heat from continuously withdrawn strand is taken away by the water-cooled jacket surrounding the mould, and the metal solidifies. Then solidification continues with secondary cooling, where the cast structure is additionally cooled in the air with help of water sprays. During solidification, the solidified shell is exposed to thermomechanical stresses, which can cause many casting defects. In the case of square billets, due to nonuniform shell solidification (i.e. nonuniform heat removal in the mould), it can be rhombic distortion (i.e. rhomboidity), which can lead to occurrence of off-corner cracks [1, 2] and twisting of the billets during plastic deformation (i.e. rolling) [3]. Generally, relative diagonal difference is used as a measure of rhomboidity of billets [1]:

$$R = 2\frac{|d_1 - d_2|}{d_1 + d_2} \tag{1}$$

where $d_1$and d_2 are the lengths of the opposite diagonals of the rhombus.

The rhomboidity of the billets is affected by the following parameters [1, 2, 4, 5]:

- steel chemical composition [6],
- casting temperature,
- casting speed,
- mould (i.e. primary cooling):
  - chemical composition,
  - mould thickness [7, 8],
  - mould tapper [7, 8],
  - mould support,
  - water jacket geometry and its alignment [9],
  - operation (e.g. oscillation, water flow, water quality) [9],
- secondary cooling:
  - water quality,
  - nozzles geometry,
  - nozzles assembly,
  - water pressure.

Researches can be divided into measurements and model calculations of the temperature field based on the melt velocity field (e.g. [1, 2]). During the measurements, the rhomboidity and/or temperature of the solidified shell are measured [1, 4, 7, 8, 10].

In this paper the improvement of rhomboidity of continuously cast billets in an industrial environment is presented. A wide range of influencing parameters, not only chemical composition but also casting parameters, have been used to predict of rhomboidity of continuously cast billets for several hypoeutectoid steel grades. Linear regression and genetic programming were used for modelling. At the beginning of the paper, the results of rhomboidity measurements and the influencing parameters are presented. Next, the prediction of rhomboidity of continuously cast billets using linear regression and genetic programming is presented. The results of the optimization of the continuous casting process are also presented and implemented into practice. The casting parameters for 42CrMoS4 steel grade, which is one of the most problematic steel grades in Štore Steel Ltd. in terms of surface defects occurrence, were optimized. Finally, conclusions and future work are highlighted.

2. Materials, methods, and experimental results

Štore Steel Ltd. is one of the major flat spring steel producers in Europe. More than 1000 steel grades with different chemical composition are produced. The main steps of the production include the following steps: melting of the scrap using electric arc furnace, tapping, ladle treatment, and continuous casting of the billets. The cooled billets are reheated and rolled in the rolling plant. The rolled bars can be subjected to additionally production operations.

Since March 2016, a new two strand continuous casting machine with a radius of 9 m has been in use (Fig. 1). Solidification of the melt takes place during primary cooling in water cooled copper mould, secondary cooling with water sprays, and tertiary radiation in air cooling.

Secondary cooling consists of 3 zones. The spray ring in zone 1 is connected directly below the mould support. It consists of 3 rows with spray nozzles which allow a uniform cooling of the billet when it leaves the mould. The upper row is equipped with 8 nozzles, the lower two rows with 4 nozzles.

The spray ring system in zone 2 is mounted on the structure in the cooling chamber. It consists of 2 parts – zone 2a and zone 2b. Zone 2a and 2b consist of 8 and 6 rows with spray nozzles, respectively. 5 rows are installed in zone 3. All rows are equipped with 4 nozzles.

The continuous casting machine and its cooling zones are schematically presented in Fig. 1.

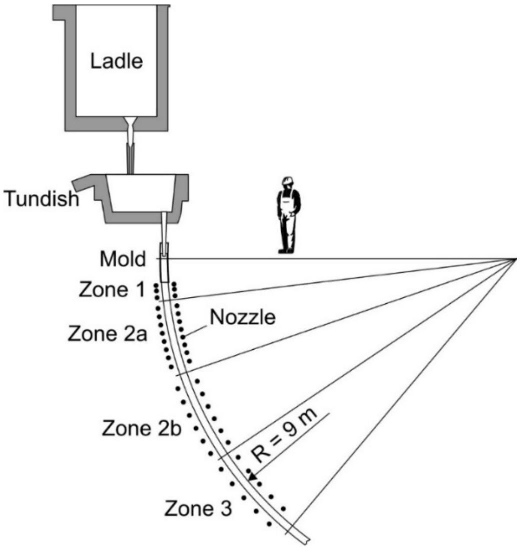

Fig. 1 The continuous casting machine and its cooling zones

The company uses in-house developed computer vision system for measurements of rhomboidity. Before entering the cooling bad, each billet is photographed, analyzed, selected features automatically recognized (e.g. billet corners) using computer vision algorithms and finally calculated relative diagonal-difference is stored in the informational system. The in-house developed computer vision system for measurement of rhomboidity of billets is presented in Fig. 2.

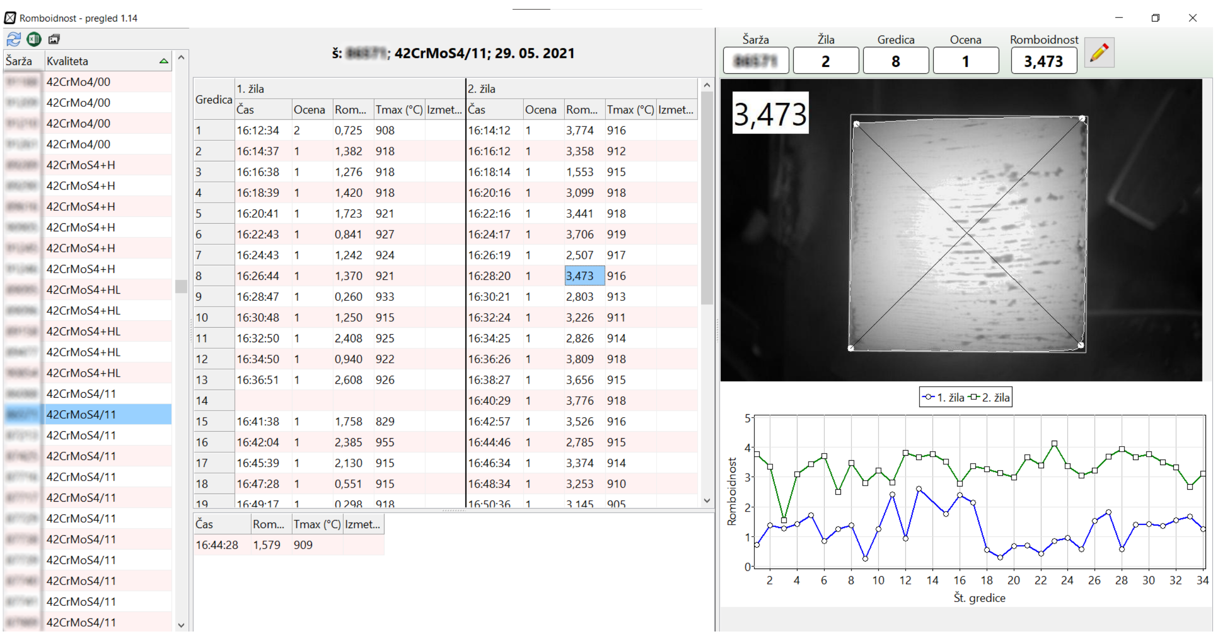

Fig. 2 In-house developed computer vision system for measurement of rhomoboidity of billets in Štore Steel Ltd.

From January 2022 to September 2022, 2088 batches was produced (64 different hypoeutectoid steel grades), and as a result, 109514 billets were cast in Štore Steel Ltd. To reduce the rhomboidity of continuously cast billets following parameters were gathered:

- Chemical composition. The content of carbon, silicon, manganese, sulfur, chromium, molybdenum, nickel and vanadium were taking into account. Chemical composition influence on material properties also during solidification (e.g. shrinkage, tensile strength).
- Casting parameters were:
  - Average casting temperature (°C). Casting temperature influences the thermal field in the mould, which influence the heat removal and solidification.
  - Mould water flow (l/min]. The highest heat removal occurs in the mould, where thermomechanical behavior influences on shell solidification.
  - Average difference between input and output mould cooling water temperature (°C). This temperature difference is a measure of efficiency of heat removal from the mould (i.e. primary cooling). The mould is cooled with the water. The heating up of the cooling water flowing through the mould indicates the efficiency of heat removal, which influences the thermomechanical behavior during solidification.
  - Mould metal level (%) expressed as a ratio between operational height of the melt level in the mould and length of the moud (mould is 1 m long copper tube). Delicate melt level movement influences on uniform shell solidification. Nonuniform shell formation leads to rhombic distortion.
  - The average cooling water pressure (bar) and flow (l/min) in the first (directly below the mould) and the second zone of secondary cooling. The melt primarily solidifies in the mould. After exiting the mould, the strand is cooled by water sprays, where water flux can be automatically set, varying water pressure/flow. Secondary cooling also influences on thermomechanical behavior during solidification.
- The rhomboidity of continuously cast billets (%) was determined using in-house developed computer vision system.

The average values and standard deviations of gathered influential parameters are presented in Table 1.

Table 1 Minimal and maximal values of gathered parameters

Parameter	Label	Average	Standard deviation
Carbon content (%)	C	0.40	0.152
Silicon content (%)	SI	0.38	0.330
Manganese content (%)	MN	0.98	0.270
Sulfur content (%)	S	0.02	0.019
Chromium content (%)	CR	0.66	0.444
Molybdenum content (%)	MO	0.06	0.067
Nickel content (%)	NI	0.21	0.300
Vanadium content (%)	V	0.06	0.051
Average casting temperature (°C)	CASTING_TEMPERATURE	1528.71	16.978
Mould water flow (l/min)	MOULD_WATER_FLOW	1835.71	77.142
Average difference between input and output mould cooling water temperature (°C)	MOULD_WATER_DELTA_TEMPERATURE	7.36	0.757
Mould metal level (%)	STEEL_LEVEL	78.09	0.932
The average cooling water flow in the first zone of secondary cooling (l/min)	ZONE1_WATER_FLOW	32.80	3.432
The average cooling water pressure in the first zone of secondary cooling (bar)	ZONE1_WATER_PRESSURE	2.21	0.504
The average cooling water flow in the second zone of secondary cooling (l/min)	ZONE2_WATER_FLOW	50.72	3.981
The average cooling water pressure in the second zone of secondary cooling (bar)	ZONE2_WATER_PRESSURE	2.20	0.482
Rhomboidity (%)	RHOMB	1.36	1.012

Table 2 Analyzed hypoeutectoid steel grades and number of continuously cast billets

Steel grade	Number of continuously cast billets	Steel grade	Number of continuously cast billets
51CrV4	26684	60MnSiCr4	454
C45S	7387	30MnB5	441
16MnCrS5	6694	30CrNiMo8	437
20MnV6	5805	15CrNi6	338
46MnVS5	5442	52SiCrNi5	315
C45	4363	55Si7	265
C50	3880	30NiCrMoV	252
30MnVS6	3542	20NiCrMo2	234
52CrMoV4	3454	37CrV3	230
38B3	3045	100Cr6	166
S355J2	2496	30CrMnV	153
28MnCrB7	2205	65Si7	153
20MnCrS5	1798	50CrMo4	144
16MnCr5	1729	45Mn5S	117
25CrMo4	1346	C35	116
34CrNiMo6	1190	31CrMoV9	110
28MnCrNiB	1115	15NiCr13	106
42CrMoS4	1113	C75	102
42CrMo4	1112	38MnVS5	98
18CrNiMo7-6	1001	50Mn7	97
23MnNiCrMo5-2	985	20NiMoCr6-5	96
61SiCr7	977	36MnVS4	93
38MnVS6	861	70MnVS4	87
20CrMoS5	742	54SiCr6	78
16NiCrS4	640	20MoCrS4	68
31CrV3	588	C15	62
P460NH	516	S235JR	51
C22	516	41CrS4	50
20MnCr5	505	55Cr3	49
18CrMo4	476	60SiMnMoV	47
100Cr6+S	461	25CrMoS4	46
C60	455	S235J2	43

Table 2 shows 64 analyzed hypoeutectoid steel grades and number of continuously cast billets.
Fig. 3 shows the average rhomboidity and its standard deviation of continuously cast billets of 20 most problematic hypoeutectoid steel grades.

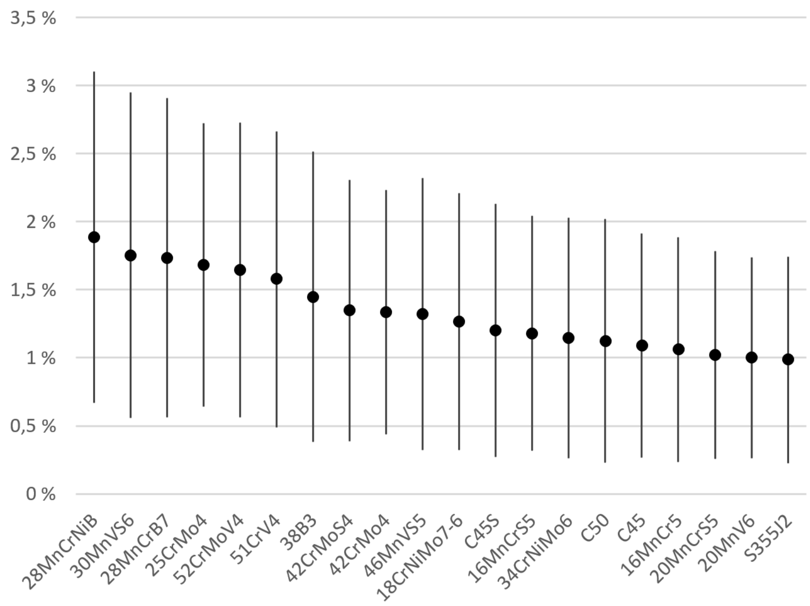

Fig. 3 The average rhomboidity and its standard deviation of continuous cast billets of 20 most problematic hypoeutectoid steel grades

3. Results and discussion

Based on the collected data (Table 1), the prediction of rhomboidity of continuously cast billets was conducted. In this paper, two methods are used to support the final decisions more reliably: linear regression approach and the genetic programming evolutionary computational method. The average deviation between predicted and experimental data was selected as the fitness function expressed as:

$$\Delta = \frac{\sum_{i=1}^{n} \left| RHOMB_i - RHOMB'_i \right|}{n}, \quad (2)$$

In Eq. 1, n is the size of the monitored data, where $RHOMB'_i$ and $RHOMB_i$ are the actual and the predicted actual rhomboidity of continuously cast billets, respectively.

3.1 Modelling of rhomboidity of continuously cast billets using linear regression

Based on the linear regression results, we realized that the model significantly predicts the rhomboidity of continuously cast billets ($p < 0.05$, ANOVA). Additionally, only 0.048 % of total variances can be explained by independent variables variances (R-square). All parameters are significantly influential except the mould metal level (STEEL_LEVEL), and the average cooling water flow in the first zone of secondary cooling (ZONE1_WATER_FLOW) ($p > 0.05$).

The obtained linear regression model is:

$$\begin{gathered} \mathrm{RHOMB} = -0.426 \cdot \mathrm{C} + 0.112 \cdot \mathrm{SI} + 0.189 \cdot \mathrm{MN} - 1.365 \cdot \mathrm{S} + 0.035 \cdot \mathrm{CR} + 0.461 \cdot \mathrm{MO} - 0.111 \cdot \mathrm{NI} - \\ 0.271 \cdot \mathrm{V} - 0.002 \cdot \mathrm{CASTING\_TEMPERATURE} + 0.002 \cdot \mathrm{MOULD\_WATER\_FLOW} - 0.0004 \cdot \\ \mathrm{MOULD\_WATER\_DELTA\_TEMPERATURE} + 0.201 \cdot \mathrm{STEEL\_LEVEL} + 0.010 \cdot \mathrm{ZONE1\_WATER\_FLOW} + \\ 0.168 \cdot \mathrm{ZONE1\_WATER\_PRESSURE} - 0.062 \cdot \mathrm{ZONE2\_WATER\_FLOW} - 0.086 \cdot \\ \mathrm{ZONE2\_WATER\_PRESSURE} + 6.156, \end{gathered} \quad (3)$$

The average deviation from experimental data is 6.23 %. The calculated influences of individual parameters on the rhomboidity of continuously cast billets while separately changing individual parameter within the individual parameter range are shown in Fig. 4. While overlooking significant influences, it seems that the mould metal level (STEEL_LEVEL) and the average cooling water flow in the second zone of secondary cooling (ZONE2_WATER_FLOW) are most influential.

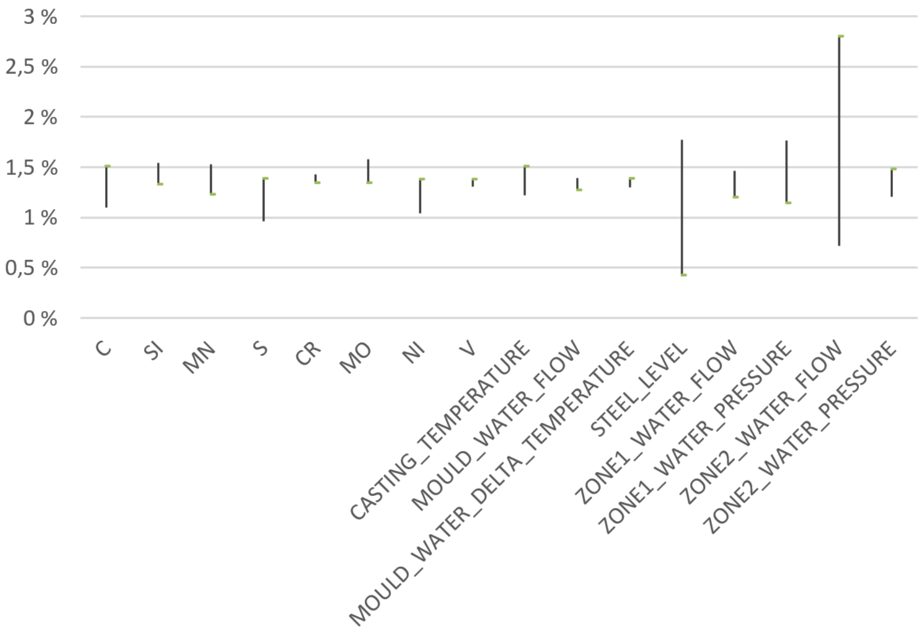

Fig. 4 The calculated influences of individual parameters on the rhomboidity of continuously cast billets based on linear regression model

3.2 Modelling of rhomboidity of continuously cast billets using genetic programming

Genetic programming is a machine learning approach that mimics the natural biological evolution of natural systems. Genetic programming is a general evolutionary optimization method similar to genetic algorithms. Both methods are successfully using to solve very different problems in engineering fields and in many other areas (11-14). In genetic programming, the organisms that undergo adaptation are in fact mathematical expressions (models) of various sizes and contents [15-17]. The content depends on the nature of the problem we are solving. These models consist of the selected and/or defined functions (e.g. mathematical operations of addition, subtraction, multiplication, division) and terminals (e.g. independent input parameters, and random floating-point constants). In the initial generation, random models (i.e. computer programs) of various forms and lengths are generated. In subsequent generations, models are modified by the genetic operations, such as crossover and mutation. After the completion of the variation of the computer programs, a new generation is obtained. During the simulated evolution, each model is evaluated. In most cases, we use experimental data and fitness function for evaluation of models. The iterative process continues until a model that meets the set criteria is obtained.

For the purpose of this research, an in-house genetic programming system [18] developed in AutoLISP was used. The following evolutionary parameters were used. The genetic operations of reproduction and crossover were used in the population size of 1000, maximum number of generations was set to 200, probability of reproduction was 0.4, probability of crossover 0.6, and minimum and maximum permissible depth of models in the initial population and after execution of crossover operation was 2 and 6, respectively. For selection of organisms, the tournament method with tournament size 7 was used. One hundred independent runs were caried out. The best mathematical model for prediction of the rhomboidity of continuously cast billets obtained from 100 runs of genetic programming system is:

$$\mathrm{RHOMB} = \frac{1}{\mathrm{ZONE1\_WATER\_FLOW}}\Bigg(MN - S - 0.014\left(\frac{C}{S} + S + \frac{C^2}{S\cdot SI}\right)\left(\frac{C}{MN} + \frac{\mathrm{ZONE1\_WATER\_PRESSURE}}{\mathrm{ZONE1\_WATER\_FLOW}}\right) + \frac{\left(CASTING\_TEMPERATURE - C - \frac{C}{SI}\right)(C + MN + ZONE1\_WATER\_FLOW)}{C - \frac{C^2}{MN\cdot S} + CASTING\_TEMPERATURE - ZONE1\_WATER\_FLOW + \frac{ZONE1\_WATER\_FLOW}{SI}}\Bigg). \tag{4}$$

The average deviation from experimental data produced by the model in Eq. 4 was 5.79 %. The model obtained by genetic programming was 7.52 % better than the one obtained using linear regression. The calculated influences of individual parameters on the rhomboidity of continuously cast billets while separately changing individual parameter within the individual parameter range are shown in Fig. 5. Based on calculated influences it seems that beside chemical composition the average cooling water flow in the first zone of secondary cooling (ZONE1_WATER_FLOW) is most influential. Please mind that content of Cr (CR), Mo (MO), Ni (NI), V (V), average casting temperature (CASTING_TEMPERATURE), mould water flow (MOULD_WATER_FLOW), average difference between input and output mould cooling water temperature (MOULD_WATER_DELTA_TEMPERATURE), mould metal level (STEEL_LEVEL), the average cooling water flow (ZONE2_WATER_FLOW) and pressure (ZONE2_WATER_PRESSURE) in the second zone of secondary cooling are missing in the Eq. 4. Based on this fact, we can conclude that natural selection and crossover operations select the components (i.e. functions or terminals) of mathematical expressions which best describe the collected data.

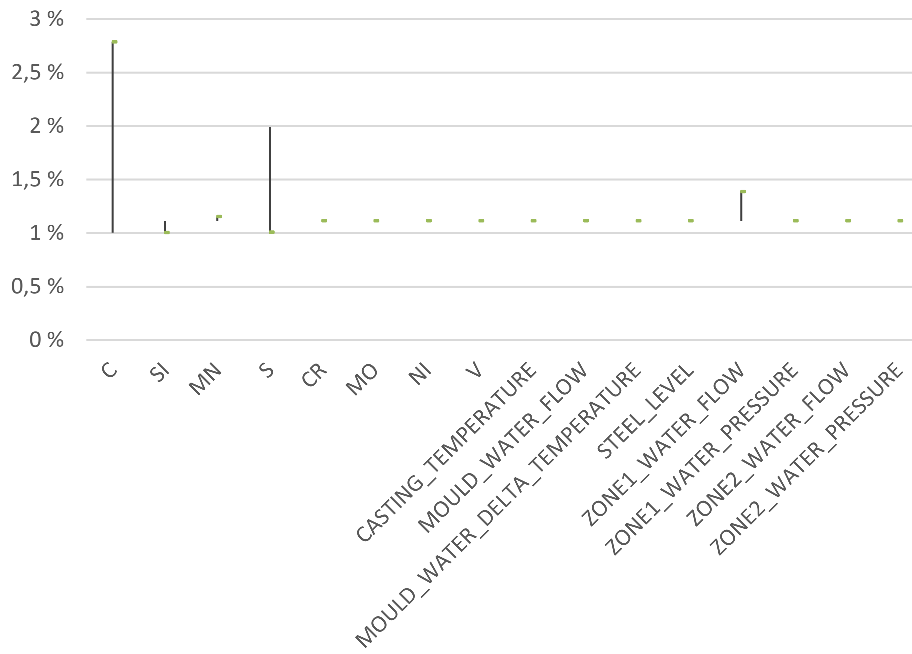

Fig. 5 The calculated influences of individual parameters on the rhomboidity of continuously cast billets based on genetic programming model

3.3 Modelling results and validation

42CrMoS4 steel grade as special structural steel used for highly stressed components for the automotive industry and mechanical engineering (e.g. shafts, connecting rods, crankshafts, screws) is one of the most problematic steel grades in Štore Steel Ltd. in terms of surface defects occurrence. The scrap rate after automatic control line examination of rolled material reaches up to 25 %. As a result, the optimization of the casting parameters was conducted to improve rhomboidity of continuously cast billets. The off-corner cracks and rhomboidity of continuously cast billet of 42CrMoS4 steel grade are presented in Fig. 6. Off-corner cracks at obtuse corners are indicated by arrows.

Based on modelling results 9 batches (419 billets) of 42CrMos4 were cast in September 2022 with 10 % higher water pressure in the first zone of secondary cooling (from 2.41 bar to 2.67 bar). The rhomboidity of continuously cast billets improved for 18.54 % (from 1.43 % to 1.21 %).

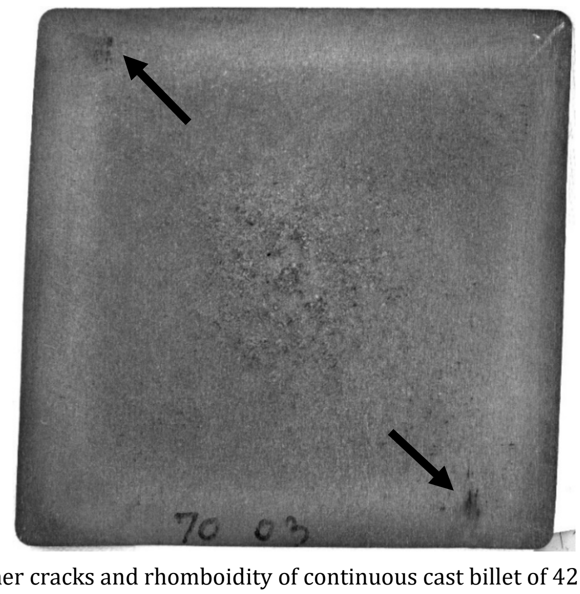

Fig. 6 The off-corner cracks and rhomboidity of continuous cast billet of 42CrMoS4 steel grade

The average deviation from experimental data (9 batches, 419 billets of 42CrMoS4 steel grade) of linear regression and genetic programming model for rhomboidity of continuously cast billets are practically the same 0.60 % and 0.59 %, respectively.

4. Conclusions

In this paper, the improvement of rhomboidity of continuously cast billets in industrial environment is presented. The wide range of influencing parameters, not only chemical composition but also casting parameters, were used for prediction of rhomboidity of continuously cast billets for several hypoeutectoid steel grades. These are: content of carbon, silicon, manganese, sulfur, chromium, molybdenum, nickel and vanadium, average casting temperature, average difference between input and output cooling water, melt level, average cooling water flow and pressure in the first and second zone of secondary cooling. The in-house developed computer vision system for measurement of rhomboidity of continuously cast billets was used which is installed in the steel plant before cast billets enter the cooling bad. The relative diagonal difference was used as a measure of rhomboidity of billets.

To predict the rhomboidity of continuously cast billets, a data of 2088 cast batches (64 different hypoeutectoid steel grades), 109,514 billets, produced from January 2022 to September 2022 in were used.

Based on linear regression results all parameters except mould metal level and the average cooling water flow in the first zone of secondary cooling ($p > 0.05$) are significantly influential. Based on genetic programming results beside chemical composition only the average cooling water flow in the first zone of secondary cooling is influential.

42CrMoS4 steel grade is one of the most problematic steel grades in Štore Steel Ltd. in terms of surface defects occurrence. The scrap rate after automatic control line examination of rolled material reaches up to 25 %.

Based on modelling results 9 batches (419 billets) of 42CrMos4 were cast in September 2022 with 10 % higher water pressure in the first zone of secondary cooling (from 2.41 bar to 2.67 bar). The rhomboidity of continuous cast billets improved for 18.54 % (from 1.43 % to 1.21 %). The average deviation from experimental data (9 batches, 419 billets of 42CrMos4 steel grade) of linear regression and genetic programming model for rhomboidity of continuously cast billets are practically the same 0.60 % and 0.59 %, respectively.

In the future, secondary metallurgy (i.e. ladle treatment) parameters, refractory material and mould wear-out, strand temperature and other geometrical features of continuously cast billets (e.g. depressions, concavity) will be also taken into account in order to improve the modelling performance.

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