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Reducing scrap in long rolled round steel bars using Genetic Programming after ultrasonic testing

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A B S T R A C T

At Štore Steel Ltd., continuously cast billets (180 mm × 180 mm) are reheated and rolled after cooling to room temperature. Hot-rolled bars are controlled as they cool to room temperature in specially designed cooling chambers, minimizing residual stresses and the development of pre-existing surface and internal defects. The bar ends can be additionally covered with insulating material. The cooled, rolled bars undergo examination using automated control lines to detect surface and internal defects, which primarily originate from the casting process. Internal defects are identified using ultrasonic testing. Between January 2022 and June 2023, 1550.0 tons of 61SiCr7 rolled bars, with diameters ranging from 53 mm to 72 mm and lengths from 7010 mm to 7955 mm, were examined using ultrasonic testing. The scrap was 109.6 tons (7.07 %). After collecting data on chemical composition (C, Si, Mn, Cr, Mo, Ni content), the casting process (casting temperature, cooling water pressure and flow in the first, second, and third zones of secondary cooling, as well as the temperature difference between input and output mould cooling water), and rolled bar geometry (diameter, length), scrap modelling after ultrasonic testing was carried using genetic programming. The genetic programming model suggested reducing the length of the rolled bar. Due to length multiplication, it was possible to reduce the rolled bar length from the initial lengths of 7010-7955 mm to the current lengths of 4558-6720 mm in June 2023. Based on this adjustment, a new production of rolled bars was established. By August 2024, 1251.9 tons of 61SiCr7 rolled bars were produced with the mentioned length adjustments. These rolled bars were subsequently examined using ultrasonic testing. The scrap was reduced by nearly 14 times, amounting to only 8.1 tons (0.64 %).

A R T I C L E I N F O

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1. Introduction

In the steel industry, the solidified steel is usually cooled to room temperature, additionally heated and hot deformed. Warm deformation is usually conducted during rolling. Rolled material is often further processed, either through heat treatment or mechanical methods. Consequently, the quality of the cast semi-finished product directly impacts the quality of the rolled and subsequently processed material. Thermo-mechanically induced defects, which may arise during or after plastic deformation and originate from the solidification process, can be minimized or eliminated either by addressing their root causes (e.g., melt preparation, casting parameters) [1-3] or reducing the consequences of the post-processed material (e.g., reduction of residual stresses, heat treatment, appropriate deformation during deformation) [4-7].

A review of the literature reveals that research on the deformation of cast semi-products with surface and internal defects, as well as their post-processing, has been ongoing for several decades [6-8]. However, investigating the behaviour of surface and internal defects in cast semi-finished products during and after deformation, particularly in industrial environments, continues to be a significant priority.

The authors in [7] analysed the influence of the orientation of surface and internal defects of continuously cast steel ingots on occurrence of defects on rolled material. Smooth flat rolls were used for the deformation process. They found that with an optimal orientation angle of the internal defects, their complete elimination is achievable.

Similarly, in [9], the authors analysed the influences of previously deformed continuously cast billets of chromium steel grades on the structure and properties of seamless pipe produced with radial-shear rolling in Pervoural'sk New Pipe Plant JSC. Their analysis of the cast macrostructure and the seamless pipe microstructure revealed that grain refinement depends on the preliminary deformation and the resulting changes in the cast macrostructure, which can be further adjusted through heat treatment. Accordingly, the required properties of seamless pipe can be achieved.

The authors in [8] describe the optimization of groove geometry, which influences the occurrence of ductility cracks during hot rolling of the remaining brittle dendritic macrostructure from the solidification process. Based on finite element simulations, the changes of the groove geometry have been made to reduce strains and stresses that promote crack openings. As a result, ductility cracks were no longer occurred.

A similar approach was used in [10], where the 3D finite element method was used to analyze the effect of stresses occurring during the three-roll planetary rolling process on existing internal voids and newly formed internal cracks. Furthermore, experimental rolling of bismuth-containing austenitic stainless steel bars was performed. The study found that the most important parameters were rolling elongation and temperature. Rolling elongation is primarily influenced by discontinuous contact between the rolls.

The article [11] investigates cross-wedge rolling of Inconel 718 for aero-engine blades to reduce internal defects. The grain size, heating temperature and rolling speed were monitored. The study found that defects nucleate at the interface between carbide particles and the matrix, subsequently propagating along chain carbides or grain boundaries. Based on sulphur addition, the grain size was reduced, the heating temperature was selected to range from 950 °C to 1020 °C, and the rolling speed was increased. The individual influences of gathered parameters were also calculated and the optimal values selected.

The authors of the study [12] attempted to analyse the occurrence of lamination during forming of seamless tube or pipe. Lamination is essentially a subsurface or surface defect that affects the inner or outer diameter of tube. Lamination can cause additional crack propagation. These types of defects are not easily detected through nondestructive testing. The recrystallization temperature, soaking time, furnace temperature, process parameters and mechanical properties were monitored to predict the surface quality of the final product. Analytical models were used. It was found that process parameters have a significant impact during production of seamless tube.

The influence of process parameters on the occurrence of asymmetrical camber defects during hot rough rolling of plate shapes was studied in [13]. The serial production data from the Xichang Steel was analysed. An Interpretable Prediction Model and Shapley additive explanation models were used to predict the occurrence of asymmetrical camber defects for two steel grades (Q335B and ST12). The theoretical analyses were consistent with the obtained models. The authors also prepared a detailed process optimization plan.

In [14], an attempt to reduce surface cracks during hot charging of high-strength, low-alloy steel thick plates is presented. Hot charging is the processes in which hot cast products (e.g., billets, slabs) are directly transported (without cooling down and reheating) from the steel plant to the rolling mill. Laboratory reports indicated that the presence of austenite in the microstructure significantly increased the size of recrystallized austenite grains, contributing to grain size non-uniformity. Based on the data on microstructure, charging temperature, and recrystallized austenite content, it was determined that the root cause of surface cracks was the presence of recrystallized austenite. As a result, the hot charging process was optimized. Based on the effort applied, the surface cracks were reduced from 7.38 % to 0.12 %.

The paper [15] presents the evolution of surface cracks that were already present on the cast semi-finished product during the rolling of heavy plates made of carbon-manganese steel. Cut samples of both the cast semi-finished product and the heavy plates were used for microstructural analysis. Additionally, electron microscopy was employed. All analyzed defects exhibited decarburization, indicating that they were present on the cast semi-finished product prior to rolling. To reduce the propagation of existing defects and prevent the occurrence of additional defects, a change in processing parameters was proposed.

This article presents an attempt to reduce the formation of internal defects or the development of defects originating from the casting process using genetic programming. The article begins with an overview of the production and rolling of 61SiCr7 rolled bars, ranging from a diameter of 53 mm to 72 mm and a length of 7010 mm to 7955 mm. After collecting data on chemical composition, casting process, and rolled bar geometry, the article describes in detail the modelling of scrap after ultrasonic testing using genetic programming. Following the modelling results, efficient practical implementations are presented, and future work is suggested in the conclusion.

2. Materials and methods

2.1 Materials and experimental setup

Production at Štore Steel plant starts with the scrap melting in an electric arc furnace, tapping, ladle treatment (i.e. secondary metallurgy) and continuous casting of billets (180 mm × 180 mm). The billets can be additionally heat-treated or control cooled under hoods. The cast billets are then reheated and rolled in the rolling plant using three rolling stands. The first two stands are duo reversible stands (800 mm and 650 mm diameter rolls), and the final continuous rolling line (460 mm diameter rolls) consists of 6 horizontal and 4 vertical stands. The cooling bed is equipped with the hoods that are adjusted according to the steel grades and the geometry of the rolled bars. The bars can be stacked individually or in pairs in cooling bed. After leaving the cooling bed, the rolled bars are cut according to the customer requirements and automatically bonded in the bundle. The bundles are transported by overhead cranes to additional cooling chambers. When the bars enter the cooling chamber, the temperature of the material is at least 500 °C. The bar ends are additionally covered with insulation material. After at least 24 hours of cooling in the chambers, the bars can be straightened, examined for internal soundness and surface quality, cut, sawed, chamfered, drilled, and peeled.

Rolled round bars can be examined (internal and surface control) using an automatic control line. Internal defects are detected using the Karl Deutsch ECHOGRAPH Ultrasonic Flaw Detector. The root causes of internal defects are typically shrinkage porosity, centre porosity, and segregations, which are linked to the solidification process – in our case, the continuous casting process. The introduction of additional stresses (e.g., bar end cutting, straightening, cooling, heating) and the presence of residual stresses increase the likelihood of internal cracking in the rolled bars. Fig. 1 shows rolled round bars with insulating material (cloths) in a cooling chamber. The ends of the three longer bars in Fig. 1 are not covered with insulating material, increasing the risk of thermally induced cracking during cooling in the chamber.

61SiCr7 is commonly used for heavy-duty springs (e.g., flat, round, and helical), as well as stabilizers and torsion bars. Between January 2022 and June 2023, 1550 tons of 61SiCr7 rolled bars, with diameters ranging from 53 mm to 72 mm and lengths from 7010 mm to 7955 mm, were inspected using an automatic control line and the Karl Deutsch ECHOGRAPH Ultrasonic Flaw Detector. A total of 152 instances were recorded, where the inspected quantity of an individual product varied from 0.8 tons to 37 tons. The scrap rate varied from 0 % to 100 %. The total scrap amount was 109.6 tons, accounting for 7.07 % of the total. To reduce the occurrence of internal defects of 61SiCr7 steel, several parameters were gathered:

- Chemical composition: Content of carbon (C), silicon (Si), manganese (Mn), chromium (Cr), molybdenum (Mo) and nickel (Ni) (%).
- Casting parameters:
  - The average temperature of the melt in tundish (TEMP) (°C).
  - The average difference between input and output mould cooling water temperature (DELTAT) (°C).
  - The average cooling water pressure (bar) and flow (l/min) in the first (directly below the mould) (Z1P, Z1Q), second (Z2P, Z2Q) and third zone (Z3P, Z3Q) of secondary cooling.
- Rolled bar diameter (DIA).
- Rolled bar length (LONG).
- Scrap ratio after ultrasonic testing using Karl Deutsch ECHOGRAPH Ultrasonic Flaw Detector (i.e. ratio between scrap and examined material quantity).

Based on gathered data, a correlation between influential parameters and the scrap ratio using genetic programming was established.

Fig. 1 The rolled round bars with insulation material (cloths) in the cooling chamber

2.2 Used methods

The scrap ratio after ultrasonic testing with Karl Deutsch ECHOGRAPH Ultrasonic Flaw Detector was predicted using genetic programming, a method belonging to the field of evolutionary computation.

Evolutionary computation is inspired by natural evolutionary processes such as selection, crossover, and mutation. Two of the most well-known methods in evolutionary computing are genetic algorithms and genetic programming. Genetic algorithms focus on finding optimal solutions by simulating evolutionary processes, where solutions evolve over generations. Genetic programming is an extension of this, where computer programs (i.e., predictive models for description of the studied system) themselves are generated and evolved to solve specific tasks. These methods are highly versatile and can be applied across various fields, including optimization, machine learning, prediction, engineering, and data analysis, as they allow for the discovery of solutions to complex problems without the need for predefined solutions [19-22].

In genetic programming, the computer programs (e.g., predictive models) consist of genes that can be selected functions (e.g., essential arithmetical functions), selected input variables, and random constants. For more details on genetic programming, please refer primarily to sources [16-18]. Based on selected genes, random mathematical expressions are built at the beginning of the simulated evolution. For this research, basic arithmetic operations (i.e., addition, subtraction, multiplication, and division) were utilized as functions. Selected input variables (parameters) included factors such as carbon content (C), the average difference between the input and output mould cooling water temperatures ($DELTAT$), rolled bar diameter (DIA), etc. A comprehensive list of variables is provided in Subsection 2.1 (since they are now considered as variables, they are presented in italics). Predictive models are constantly being modified with genetic operations during several generations. In the research, we used crossover and mutation operations to modify organisms. The reproduction operation was incorporated as a standard mechanism to enhance the probability of higher-fitness organisms progressing to subsequent generations. After the completion predictive models' modification, a new generation is obtained. All predictive models are evaluated using the fitness function. In this study, the average of absolute differences between the actual and predicted scrap ratio was chosen as the fitness function. The process is repeated until the termination criterion is fulfilled. For this research, the termination criterion was defined as reaching the maximum prescribed number of generations.

3. Results and discussion

We developed a general-purpose genetic programming system to model predictive models [23-26]. This self-developed system was designed to handle a wide range of tasks, enabling the effective evolution of models tailored to specific prediction needs. After performing 100 runs of the genetic programming system, we analysed the results and obtained the best predictive model for predicting the scrap ratio after ultrasonic testing. The resulting model is as follows.

$$\frac{DIA}{DIA-\dfrac{\left(Mo+\dfrac{LONG}{-Cr+\dfrac{DELTAT}{Ni}}+2\,Si+Z2P+Z3P+\dfrac{Cr\,Z3P}{DIA\,(DELTAT+Z2Q)}\right)\left(Mo-\dfrac{Z1P\left(DIA-\dfrac{Z3P\left(-DELTAT+Mo+\dfrac{DELTAT}{Ni}+Si+Z3P\right)}{DELTAT}\right)}{C\left(TEMP+\dfrac{LONG}{\dfrac{DELTAT}{Ni}-Z2Q}\right)}\right)}{LONG\,Mo}} \tag{1}$$

The average of absolute differences between the actual and predicted scrap rate is 5.96 %. Additionally, it is necessary to note that the genetically developed model does not contain the following parameters: $Z1Q$ (average cooling water flow in the first zone of secondary cooling), $Z3Q$ (average cooling water flow in the first zone of secondary cooling) and Mn (manganese content). Similarly, while checking the developed models from other runs obtained using genetic programming, it can be concluded that the $LONG$ (rolled bar length) is one of the top 5 (out of 16) parameters which were not excluded from the developed models. The number of excluded parameters is presented in Fig. 2.

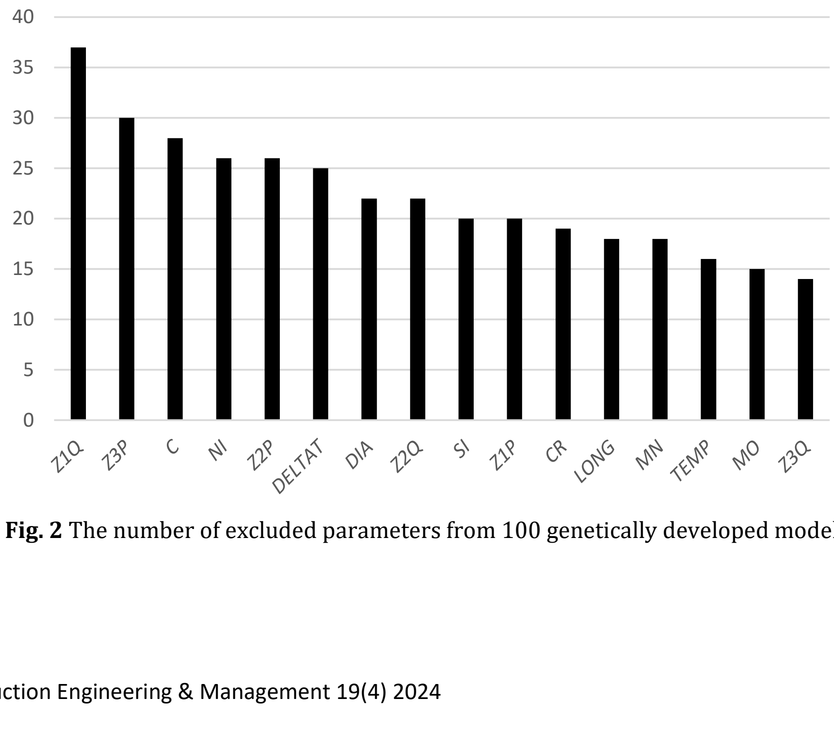

Fig. 2 The number of excluded parameters from 100 genetically developed models

Additionally, the influences of individual parameters can be calculated using a genetic programming model. When changing the values within the actual interval of individual parameters, the values of the other parameters remained the same. The results of the genetic programming model are shown in Fig. 3. The length of the rolled bars (parameter *LONG*) appears to be the most influential factor, with scrap rates ranging from 93.81 % to 100.05 %.

Based on the technical delivery conditions, required chemical composition, rolled bar diameter, post-rolling treatment in cooling chambers, the number of parameters extracted from 100 genetically developed models, and the calculated effects of individual parameters using genetic programming, the only viable option was to change the length of the rolled bars. It should be emphasized that length multiplications were possible.

For informational purposes, in this phase of the research, we envisioned shorter rolled bar lengths from 4558-6720 mm (until now, we have been producing bars with lengths of 7010-7955 mm) to be used with the obtained genetic programming model. Other parameters gathered from January 2022 to June 2023 remained the same. The genetically developed model predicted that the scrap rate would be 0.00 % (currently 7.07 %) if shorter bars were used.

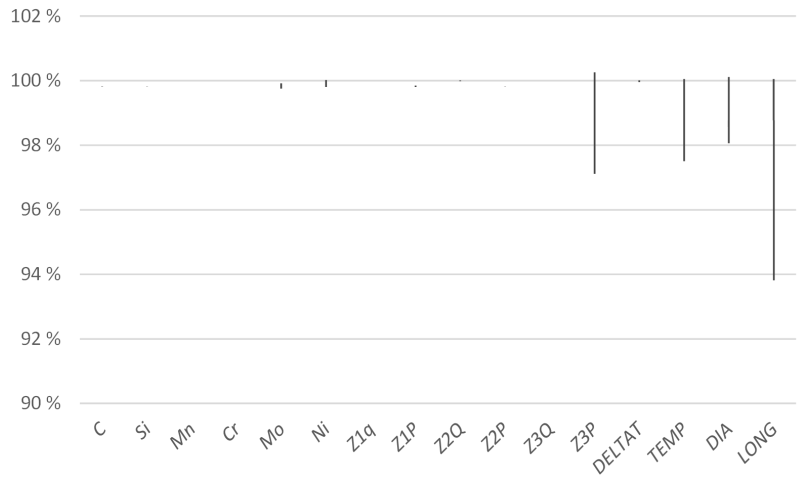

Fig. 3 The calculated influences of individual parameters using genetic programming model

Validation of modelling results

Based on the modelling results and the length multiplications, the rolled bar lengths were reduced from the initial range of 7010-7955 mm to 4558-6720 mm for all orders starting from June 2023. By August 2024, a total of 1251.9 tons of 61SiCr7 rolled bars with adjusted lengths had been examined using ultrasonic testing. As a result, scrap was reduced by nearly 14 times, amounting to only 8.1 tons (0.64 %). This result clearly demonstrates that with relatively simple measures, we can reduce the carbon footprint in the steel processing industry and thus contribute to environmental sustainability.

4. Conclusion

This paper examines the use of genetic programming to reduce internal defects in 61SiCr7 steel bars originating from the casting process. The billets are reheated, rolled, and cooled in a controlled cooling bed, followed by further treatment in cooling chambers. After cooling, the bars are inspected, straightened, and cut.

Internal defects, such as porosity and segregations, are detected using the Karl Deutsch ECHOGRAPH Ultrasonic Flaw Detector. A total of 1550 tons of 61SiCr7 bars were examined, with a scrap rate ranging from 0 % to 100 %, resulting in 109.6 tons of scrap (7.07 %).

Data on chemical composition, casting conditions, and bar geometry were used to develop a genetic programming model to predict the scrap rate. The model achieved an average error of 5.96 %, and the most influential parameter was the bar length (*LONG*). Shortening the rolled bars from 7010-7955 mm to 4558-6720 mm resulted in a predicted reduction in scrap to 0.00 %.

Since June 2023, all orders have been produced using shorter bar lengths, as suggested by the research, leading to a significant reduction in scrap by nearly 14 times. By August 2024, a total of 1251.9 tons of bars had been examined, and only 8.1 tons (0.64 %) of scrap were produced, demonstrating the effectiveness of the length adjustments in minimizing waste. This approach also significantly improves the carbon footprint, contributing to a greener and more sustainable production process.

Future plans include optimizing the cooling processes in continuous casting to improve internal quality and exploring the potential for shortening bars for other steel grades and shapes.

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