Soft annealing productivity optimization

Optimiranje produktivnosti mehkega žarjenja

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Abstract: The optimal thermo-mechanical processing in steel industry is difficult because of the multi-constituent and multiphase character of the commercial steels, variety of multi-constituent the possible processing paths, and plant specific equipment characteristics. This paper shows successful implementation of the genetic programming approach for increasing the furnace conveyor speed and consequently productivity of the heat treatment furnace in the soft annealing process. The data (222 samples covering 24 different steel grades) on a furnace conveyor speed, chemical composition of steel (weight percent of C, Cr, Mo, Ni and V) and Brinell hardness before and after the soft annealing were collected during daily production. On the basis of the monitored data a mathematical model for the hardness after the soft annealing was developed by genetic programming. According to the modeled influences on the hardness, the higher furnace conveyor speed was attempted in practice. The experimental results of the hardness after the soft annealing with the increased conveyor speed and the predictions of the mathematical model were compared within the agreement of 3.24 %. The productivity of the soft annealing process increased (from the furnace conveyor speed 3.2 m/h to 7 m/h) as a consequence of the used computational intelligence approach.

Izvleček: Zaradi težko določljivih lastnosti komercialnih jekel, raznolikosti tehnoloških poti in specifične opreme je optimalno termo-mehansko procesiranje v jeklarstvu izredno problematično. V

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članku je predstavljena uporaba genetskega pogramiranja z namenom povečati hitrost transportnega traku žarilne peči in posledično produktivnost žarilne peči in procesa žarjenja samega. Med tipično proizvodnjo so bili zbrani podatki (222 vzorcev, 24 kvalitet jekla) o hitrosti peči, kemijski sestavi jekla (masni deleži C, Cr, Mo, Ni in V) ter trdota po Brinellu pred mehkim žarjenju in po njem. Na podlagi zbranih podatkov je bil izdelan matematični model trdote po mehkem žarjenju z metodo genetskega programiranja. Glede na izračunane vplive na trdoto po mehkem žarjenju smo povečali hitrost žarjenja. Po povečanju hitrosti žarjenja se izmerjene trdote materiala ujemajo z izračunanimi v povprečju 3,24-odstotno. Produktivnost mehkega žarjenja se je povečala iz 3,2 m/h na 7 m/h kot posledica umetne inteligence.

Key words: steel, soft annealing, productivity, hardness, genetic programming, modeling

Ključne besede: jeklo, mehko žarjenje, produktivnost, trdota, genetsko programiranje, modeliranje

INTRODUCTION

There is a strong trend in steel industry for enhanced productivity, safety, and environmental friendliness of the involved processes, in parallel with the enhanced product variety and quality. In the last two decades, the thermomechanical physical models are increasingly developed for casting, rolling, and heat treatment operations.[1] However, the current state-of-the-art in physical modeling does not permit to quantitatively model the whole range of steel behavior neither from the microscopic materials science point of view, nor from the macroscopic process level. This is probably due to the multi-constituent and multi-phase character of the steel as well as due to the fact that the important physical processes took place over a huge range of length scales from the nano up to 100 m. The physical modeling is thus increasingly connected with the intelligent algorithms (such as for example artificial neural networks, evolutionary computation, swarm intelligence, artificial immune systems, and fuzzy systems) [2] which complement or replace the physical models in solving realistic industrial problems. An example of such symbiosis[3] is the continuous casting physical modeling with the evolutionary algorithm for searching the optimum casting conditions. The purpose of the heat treatment of the steels is to cause the desired changes in the metallurgical structure and thus material properties.[4] Soft annealing represents heat treatment wherein a material is altered, causing changes in its ductility and hardness. Several attempts have been made to attain the control of the above mentioned material properties at the soft annealing treatment.[5–9] The aim of the present research is to find out the possibilities of increasing the furnace productivity (speed of the furnace conveyor) at the soft annealing process. The genetic programming method is used in the present paper to establish the relations between the chemical composition of the principal alloying elements (carbon, chromium, molybdenum, nickel and vanadium), the principal process parameters (such as the speed of the furnace conveyor), and the principal material property (hardness after the soft annealing treatment). Having this relations set, more optimal conveyor speed could be easily determined with respect to the process parameter constraints, i.e. maximum possible speed of the conveyor, and product properties constraints, i.e. maximum hardness.

Genetic programming is one of the methods of the evolutionary computation.[10, 11] In the genetic programming, organisms which are more or less complicated computer programs, are subject to adaptation. The computer programs are in fact models for prediction of the hardness after the soft annealing in the present study. Many different prediction models, differing in the quality of prediction and the complexity of the structure, were obtained during the simulated evolution. Only one model out of many is discussed in the present paper.

THE HEAT TREATMENT FURNACE DESIGN AND THE EXPERIMENTAL DATA

All experimental data, used in the present paper, have been obtained from the pusher-type furnace of Štore Steel steelworks - Slovenia, one of the major spring-steel producers in Europe. The scheme of the furnace is depicted in Figure 1. The hardness after the annealing process depends on the chemical composition of the steel and the furnace process parameters. The main methodological constraint of the present paper is, according to production pace, that the production lining parameters could only be monitored and not allowed to vary. The experimental data have been thus obtained directly from the undisturbed production. The principal seven adjustable furnace process parameters are the six different temperatures of the heat treatment zones and the time of the annealing (inversely proportional to the speed of the furnace conveyor). The principal two fixed construction parameters of the furnace are the maxi-

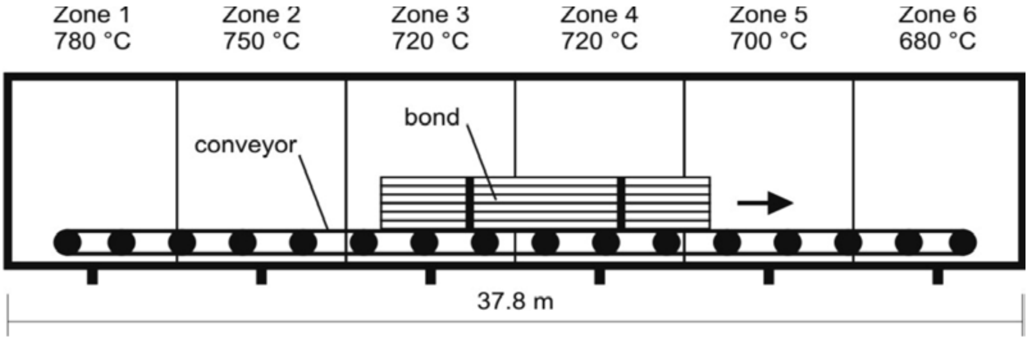

Figure 1. Heat treatment furnace with its six equidistant temperature zones

Table 1. The number of steel grade specimens and the average chemical composition

		Composition, *w*/%	C	Cr	Mo	Ni	V
#	Steel grade	Number of specimens					
1	15CrNi6	1	0.14	1.56	0.04	1.53	0
2	16MnCr5	1	0.19	1.03	0.02	0.09	0
3	17CrNiMo6	2	0.18	1.65	0.28	1.50	0
4	18 CrNi 8	1	0.19	1.95	0.02	2.01	0
5	18CrNiMo7-6	15	0.17	1.64	0.29	1.53	0.001
6	18CrNiMo7-6 HH	2	0.19	1.69	0.29	1.53	0
7	23MnNiCrMo5-2-A	12	0.22	0.49	0.21	0.47	0
8	25CrMo4	4	0.24	1.01	0.20	0.10	0
9	34CrNiMo6	28	0.36	1.61	0.22	1.60	0.003
10	41Cr4	7	0.42	1.08	0.03	0.11	0
11	42CrMo4	33	0.42	1.07	0.22	0.11	0
12	42CrMoS4	8	0.43	1.03	0.21	0.11	0
13	50CrMoS4	14	0.51	1.04	0.22	0.13	0
14	50CrV4	34	0.50	1.05	0.04	0.11	0.156
15	51CrMoV4	1	0.54	1.06	0.18	0.09	0.11
16	51CrV4	11	0.51	1.08	0.04	0.11	0.1555
17	51CrV4 HH	3	0.51	1.08	0.04	0.12	0.170
18	52CrMoV4	6	0.54	1.05	0.18	0.10	0.113
19	55Si7	16	0.57	0.29	0.04	0.12	0
20	70MnVS4	20	0.70	0.15	0.03	0.08	0.113
21	25CrMo4	1	0.24	1.05	0.21	0.14	0
22	42CrMo4	2	0.43	1.03	0.21	0.11	0
SUM		222					

mum bond specific weight 2.5 t/m and the maximum conveyor speed 7 m/h. The cross-sections of the round and flat bars in the bond varied from 43.28 mm^2 to 5676.40 mm^2. The temperature of the six heat treatment zones was kept constant in all cases (see data in Figure 1). The only influential heat treatment

Table 2. Part of the monitored data set

#	Conveyor speed [m/h]	Hardness before the soft annealing [HB]	w(C)/%	w(Cr)/%	w(Mo)/%	w(Ni)/%	w(V)/%	Hardness after the soft annealing [HB]
1	3.2	298	0.51	1.09	0.22	0.19	0	219
2	3.2	248	0.43	1.08	0.02	0.1	0	191
3	3.2	313	0.69	0.14	0.02	0.08	0.11	229
4	3.2	309	0.70	0.13	0.02	0.08	0.12	215
5	3.2	290	0.55	0.28	0.04	0.12	0	229
6	3.2	290	0.59	0.36	0.05	0.12	0	229
…	…	…	…	…	…	…	…	…
220	3.2	298	0.17	1.64	0.29	1.53	0	198
221	3.2	290	0.40	1.04	0.22	0.08	0	207
222	3.2	333	0.52	1.14	0.05	0.11	0.15	229

productivity process parameter was the speed of the furnace conveyor. The speed of the furnace conveyor was kept steady during the heat treatment of the individual bond. The required hardness of the annealed steel has to be below 260 HB before the bond steel bars are subsequently saw-cut.

The number of each steel grade specimens and the average chemical composition (mass fractions w/% of C, Cr, Mo, N and V) is represented in Table 1.

According to actual production technology only two furnace conveyor speeds of 2.5 m/h and 3.2 m/h were used for soft annealing. Brinell hardness for each data set before and after soft annealing was measured at the bar centre at the three positions per bond: once from the bar taken from the bond surface and twice from the bar taken from the middle of the bond. Then the average hardness per bond was calculated and used for modeling. Only a part of the respective monitored data set is shown in Table 2.

GENETIC PROGRAMMING MODELING OF THE HARDNESS AFTER THE SOFT ANNEALING

Genetic programming is probably the most general evolutionary optimization method.[11] The organisms that undergo adaptation are in fact mathematical expressions (models) for the hardness after the soft annealing in the present work. The prediction consists of the available function genes (i.e., basic arithmetical functions) and terminal genes (i.e., independent input parameters, and random floating-point constants). In the present case the models consist of the following function genes: addition (+), subtraction (–), multiplication (*) and division (/), and the following terminal genes: furnace conveyor speed (speed), measured *v*/(m/h), hardness before soft annealing (HB), measured in Brinell units, and chemical composition of the principal alloying elements: carbon (C), chromium (Cr), molybdenum (Mo), nickel (Ni) and vanadium (V), measured in mass fractions, *w*/%.One of the randomly generated mathematical models is schematically represented in Figure 2 as a program tree with included function genes (*, + , /) and terminal genes (Mo, speed, V, C, and a real number constant 5.1).

The following evolutionary parameters were selected for the process of simulated evolutions: 500 for the size of the population of organisms, 100 for the maximum number of generations, 0.4 for the reproduction probability, 0.6 for the crossover probability, 6 for the maximum permissible depth in the creation of the population, 10 for the maximum permissible depth after the operation of crossover of two organisms, and 2 for the smallest permissible depth of organisms in generating new organisms. Genetic operations of reproduction and crossover were used. For selection of organisms the tournament method with tournament size 7 was used. 100 independent civilizations of mathematical models for prediction of the hardness after the soft annealing have been developed.

The best obtained model for the hardness after the soft annealing is:

$$\begin{gathered}
127.132 + 19.309\,\mathrm{Cr} + \frac{\mathrm{V}\left(3.436 + \mathrm{Mo} + 4.117\,\mathrm{Ni} - \frac{\mathrm{V}}{\mathrm{Mo}}\right)}{-2.234\,\mathrm{Mo} + 2\,\mathrm{Ni} + \frac{1}{\mathrm{speed}} + \mathrm{V}} + \frac{\left(\mathrm{C} + \frac{1+\mathrm{Cr}}{\mathrm{V}}\right)\mathrm{V}}{\mathrm{Ni}\left(-1.234\,\mathrm{Mo} - 1.234\,\mathrm{Ni} + 2.845\,\mathrm{speed} - \frac{\mathrm{V}}{\mathrm{Mo}}\right)} + \\
\mathrm{C}\left(136.993 + 6.298\,\mathrm{Mo} + 38.664\,\mathrm{Ni} + 6.117\,\mathrm{V} - \frac{6\,\mathrm{V}}{\mathrm{Mo}} - \frac{\mathrm{V}}{\mathrm{Ni}} + \frac{-2.234\,\mathrm{Mo} + \mathrm{Ni} + \mathrm{V}}{\mathrm{Ni}} - \frac{-2.234\,\mathrm{Mo} + \mathrm{Ni} + 2\,\mathrm{V}}{\mathrm{Mo}}\right) + \\
\mathrm{Mo}\left(-2.234 - 2.234\,\mathrm{Mo}\left(4.117 + \mathrm{C} + \frac{\mathrm{Cr}}{\mathrm{Mo}} - 2\,\mathrm{V}\right) + \mathrm{V} + \frac{\left(\mathrm{C} + \frac{1}{\mathrm{V}}\right)\mathrm{V}}{\mathrm{Ni}\,\mathrm{speed}}\right)\left(\frac{\mathrm{Cr}}{\mathrm{Mo}} - \frac{(0.2429 + \mathrm{C})(-2.234\,\mathrm{Mo} + \mathrm{Ni} + 2\,\mathrm{V})}{\mathrm{speed}}\right) + \\
0.021\left(\mathrm{HB} + \mathrm{Mo} + \frac{2 + 2\,\mathrm{Mo} + 5.117\,\mathrm{Ni} + \frac{\mathrm{speed}\left(2\,\mathrm{C} + \frac{1}{\mathrm{Cr}\,\mathrm{V}}\right)}{\mathrm{Cr}} + \mathrm{V} - \frac{\mathrm{V}}{\mathrm{Ni}}}{-1 + 19.075\,\mathrm{Mo} + 6.117\,\mathrm{Ni} - \frac{4.117\mathrm{V}}{\mathrm{Mo}} - \frac{\left(\mathrm{C} + \frac{\mathrm{Cr}}{\mathrm{Mo}}\right)\mathrm{V}}{\mathrm{speed}} - \frac{\mathrm{V}}{\mathrm{Ni}+\mathrm{V}}}\right) + \\
2.845\left(\mathrm{speed} + \mathrm{V}\left(19.309\,\mathrm{Cr} - 1.234\,\mathrm{Mo} + \frac{\frac{\mathrm{C} + \frac{\mathrm{Cr}}{\mathrm{Ni}}}{\mathrm{speed}} + \frac{\mathrm{C} + \frac{\mathrm{Cr}}{\mathrm{V}}}{\mathrm{speed}}}{19.309\,\mathrm{Mo} + 5.117\,\mathrm{Ni} + 4.117\,\mathrm{V} - \frac{\mathrm{V}}{\mathrm{Mo}}} - \frac{4.117\,\mathrm{Ni} + \frac{\frac{\mathrm{Cr}}{\mathrm{V}} + \mathrm{C}\,(4.117 + 4.117\,\mathrm{V})}{\mathrm{speed}}}{-2.234 + 20.309\,\mathrm{Mo} + 2\,\mathrm{Ni} + \mathrm{V} - \frac{2\,\mathrm{V}}{\mathrm{Mo}}}\right)\right)
\end{gathered}$$

with the average percentage deviation of 3.24 %.

Soft annealing productivity optimization

The maximum furnace conveyor speed, declared from the furnace producer, is 7 m/h. As previously mentioned, the required hardness of the cutting material should be below 260 HB in order to satisfy the product quality requirement.

The previously mentioned results and behavior regarding the sensitivity of the furnace conveyor speed in the soft annealing process allows us to carefully (in several steps) increasing the conveyor speed up to 5 m/h and at last for 7 m/h in industrial practice. The experimental results of hardness for 13 specimens are shown in Table 3, compared with the calculated values from the computational intelligence model.

Conclusion

In this paper the possibility of the productivity enhancement of the heat treatment furnace for the soft annealing of the round and the flat steel bars in Štore Steel company was studied. The Brinell hardness after the process was measured for 24 different steel grades as a function of the furnace process parameters and steel composition.

Table 3. Measured and calculated hardness after the soft annealing

#	Conveyor Speed v/(m/h)	Hardness before softannealing	C w(C)/%	Cr w(Cr)/%	Mo w(Mo)/%	Ni w(Ni)/%	V w(V)/%	Hardness after the soft annealing (monitored) [HB]	Hardness after the soft annealing (genetic programming model) [HB]	Percentage deviation
	5.0	298.0	0.59	0.28	0.05	0.13	0.00	229	237.089	3.53 %
	5.0	464.0	0.34	1.51	0.20	1.50	0.01	229	235.528	2.85 %
3	5.0	335.0	0.53	1.13	0.05	0.19	0.14	229	236.332	3.20 %
4	5.0	438.0	0.36	1.64	0.23	1.64	0.01	229	241.571	5.49 %
5	5.0	438.0	0.34	1.51	0.20	1.50	0.01	229	234.982	2.61 %
6	5.0	339.0	0.43	1.18	0.22	0.15	0.00	215	224.551	4.44 %
7	5.0	339.0	0.43	1.18	0.22	0.15	0.00	215	224.551	4.44 %
8	5.0	309.0	0.7	0.12	0.02	0.07	0.11	215	216.467	0.68 %
9	5.0	309.0	0.7	0.12	0.02	0.07	0.11	215	216.467	0.68 %
10	5.0	309.0	0.7	0.13	0.02	0.08	0.12	215	214.519	0.22 %
11	7.0	335.0	0.55	1.14	0.03	0.12	0.15	249	237.717	4.53 %
12	7.0	313.0	0.53	1.13	0.03	0.10	0.15	239	235.34	1.53 %
13	7.0	361.0	0.54	1.08	0.17	0.09	0.12	249	250.438	0.58 %
									Average percentage deviation	2.68 %

This established an experimental data base for development of 100 models, deduced through the genetic programming methodology. Genetic programming predicts the hardness after the soft annealing with the average percentage deviation of only 3.24 %. The best genetically developed model was closely analyzed and it was established that the furnace conveyer speed is not a sensitive parameter for influencing the hardness after the soft annealing. These findings lead to the changes of the maximum furnace conveyor speed from 3.2 m/h up to 7 m/h in the production practice. The substantially higher conveyor speed did not influence the hardness of the steel after the soft annealing as expected from the model prediction. The hardness after the soft annealing was below the required hardness of 260 HB also in the case of the enhanced conveyor speed in all 13 tested cases. The agreement between the tested and the calculated data is 2.68 %. The results of the research were practically applied.

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